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WORKBOOK OF THERMAL PLUME PREDICTION. VOLUME I. SUBMERGED DISCHARGE

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Data and analyses from numerous sources constitute the backup material for this publication. An attempt has been made to unify and present the material in a format that is sufficiently simple for a non-specialist user. A number of illustrative examples are presented which demonstrate the use of each set of nomograms in practical problems.

The status of analysis at this time is not sufficiently advanced to encompass a wide range of experimentally verified predictive models. For this reason, care must be exercised when applying the generalized nomograms to specific situations. The major restrictions for each set of nomograms are outlined in the text which the user is advised to review carefully. In general, the nomograms provide meaningful qualitative information for a wide range of problems of practical interest, but their use is subject to scrutiny and proper interpretation when applied to exacting design conditions.

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EPA-R2-72-005a

August 1972

WORKBOOK OF THERMAL PLUME PREDICTION

Volume 1

Submerged Discharge

By

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PREFACE

This workbook contains computational procedures in the form of nomograms designed to satisfy several needs related to the discharge of thermal waste into large bodies of water. They provide estimates of physical spread and temperature distribution around the discharge point for the assessment of biological and physical effects of heated water. They can be used as guidelines for setting temperature standards and for monitoring. Finally, they have utility in pre-design feasibility analyses and outfall performance estimates.

Data and analyses from numerous sources constitute the back-up material for this publication. An attempt has been made to unify and present the material in a format that is sufficiently simple for a non-specialist user. A number of illustrative examples are presented which demonstrate the use of each set of nomograms in practical problems.

The status of analysis at this time is not sufficiently advanced to encompass a wide range of experimentally verified predictive models. For this reason, care must be exercised when applying the generalized nomograms to specific situations. The major restrictions for each set of nomograms are outlined in the text which the user is advised to review carefully. In general, the nomograms provide meaningful qualitative information for a wide range of problems of practical interest, but their use is subject to scrutiny and proper interpretation when applied to exacting design conditions.

This is a part of a continuing effort to present the current knowledge on predictive models to the public. As more data are obtained in the future, the nomograms will be refined and updated. This first volume is devoted to submerged discharges. The analysis of surface discharge is the subject of a separate volume to be prepared.

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LIST OF SYMBOLS, DIMENSIONLESS NUMBERS, AND NOTATIONS

A. STANDARD SYMBOLS AND DIMENSIONLESS NUMBERS

D	Jet diameter
F	Jet densimetric Froude number
	$F = \dfrac{U_j}{\sqrt{\dfrac{\rho_o - \rho_j}{\rho_o} gD}} = \dfrac{GU_j}{\sqrt{D}}$
g	Gravitational constant
G	$[\frac{\Delta\rho_o}{\rho_o} g]^{-1/2}$ plotted on Fig. F-1
H_c	Waste heat load
k	Velocity ratio $\frac{U_j}{U_o}$
L	Jet spacing on multiple jet diffuser
Q	Volumetric flow rate
r	Radial distance from plume center
S	Distance along plume centerline
S_t	Stratification number
	$S_t = \dfrac{\Delta\rho_o/D}{\Delta\rho_a/\Delta Z} \simeq \dfrac{\Delta T_o/D}{\Delta T_a/\Delta Z}$
T	Temperature
U	Velocity
W	Plume width
X,Z	Coordinates of plume centerline

Z_s	Linearized non-stratified depth defined in Fig. 6
η	$\frac{4r}{W}$
ρ	Density
θ	Discharge angle relative to horizontal
$\Delta(\ )_o$	$(\ )_j - (\ )_o$
$\Delta(\ )_c$	$(\ )_c - (\ )_a$
$\Delta(\ )_a$	$(\ )_a$ at Z_2 - $(\ )_a$ at Z_1

Subscripts

a	Ambient
c	Centerline
j	Jet
o	Ambient at discharge depth

B. SHORTHAND NOTATIONS

A three-letter code is used for convenient reference. First letter designates type of diffuser; second letter, the type of current; third letter, the degree of stratification.

Diffuser Configuration	Condition of Ambient Water			
	Non-Stratified		Stratified	
	No Current	Moving	No Current	Moving
Single Round Port	RNN	RCN	RNS	RCS
A Row of Multiple Round Ports	MNN	MCN*	MNS	MCS*

*Nomograms not presented for these cases.

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I. INTRODUCTION

Warm water diffusers are commonly classified into two broad categories, namely, surface and submerged. A surface diffuser generally produces a large zone of relatively high excess water temperature that is spread in a thin layer above the cool unmixed ambient water. While a surface diffuser can be designed to achieve a considerable degree of mixing with the ambient water, rapid mixing of warm water effluent with the ambient water is best obtained with a submerged diffuser.

A properly designed, deeply submerged diffuser can readily produce adequate mixing and dilution before the plume reaches the water surface. The factors affecting this design include (1) the diffuser configuration such as single round port, multiple round ports, or slotted port, (2) the discharge angle relative to the ambient current and gravity, (3) the discharge excess temperature (or density) above the ambient, and (4) the discharge velocity. Ambient temperature and density stratifications and the presence of ambient current all significantly contribute to rapid mixing and should be carefully considered in making plume analyses.

When analyzing plume behavior, one is usually interested in the trajectory of the plume, its width and some information concerning the local temperature within the plume along its trajectory. The plume trajectories in this book are plotted with respect to vertical and horizontal coordinates, both made dimensionless by dividing by the diffuser port diameter. The width of the plume is conventionally taken equal to four standard deviations of the local temperature distribution across the plume trajectory where this distribution is assumed to be Gaussian. The information on the plume temperature is best given for the centerline of the plume

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and expressed in terms of the excess centerline temperature difference along the trajectory divided by the excess discharge temperature difference $[\frac{\Delta T_c}{\Delta T_o}]$. In all cases, the temperature difference is calculated locally to show the excess temperature above ambient.

The trajectory, the width, and the centerline temperatures are expressed in appropriate dimensionless numbers. Furthermore, the discharge characteristics such as the velocity, excess temperature (or density), and diameter are also collected in a dimensionless form called the Froude number. The Froude number is the ratio of inertial forces due to the jet discharge velocity to the buoyant forces due to the discharge density difference with respect to the ambient. Formally, this is expressed as $F = U_j/(\frac{\Delta\rho_o}{\rho_o} gD)^{1/2}$. This number has been used extensively as a correlation parameter in plume analysis. Other dimensionless numbers found useful in correlating plume data are the ratio of the discharge velocity to the ambient velocity (k) when there is an ambient current and the stratification number describing the vertical density (or temperature) gradient within the ambient water when the ambient density is not constant with depth. The reader is advised to familiarize himself with the dimensionless parameters listed immediately behind the Table of Contents.

The reader should also review the shorthand notations (p.vii)since they will be used extensively. The three letters of the the shorthand notation refer to (1) the diffuser configuration, (2) the presence or absence of the ambient current, and (3) the presence or absence of ambient stratification, respectively. Single round port diffusers are designated by R and a diffuser consisting of a row of multiple round ports is designated by the letter M. The presence of current and stratification are designated by C and S, respectively, and their absence is designated by N. Thus, RNN refers to a single port diffuser discharging into stagnant, non-stratified ambient water as listed in the shorthand notation table. Other combinations readily follow.

The relative influence of such factors as ambient water conditions and diffuser configuration on the plume trajectory, width, and centerline excess temperature is best illustrated by the typical examples given below. These examples are obtained from the nomograms of this volume with only a slight modification in format. They are chosen only for the purpose of discussion at this point and in order to familiarize the reader with the scope of this volume quickly and with a minimum of introductory work. The discharge Froude number for all examples is taken equal to 10. The discharge angle with respect to the horizontal is equal to zero. When the ambient water is moving, the direction of the jet discharge is the same as the direction of the ambient current and the discharge velocity is equal to the ambient velocity. The stratification number when applicable is taken equal to 500. The plume width and centerline trajectories are presented first on individual Figs. 1 through 4 and the centerline excess temperature decays are plotted jointly on Fig. 5 for the purpose of comparison.

The centerline trajectory and plume width from a single port diffuser discharging into a stagnant, non-stratified body of water (RNN) is plotted in Fig. 1. The plume travels horizontally a short distance before the buoyancy forces lift it upward as shown in the plot. The plume continues to rise until it loses buoyancy or reaches the water surface. Meanwhile, the plume centerline temperature continues to decay as shown in Fig. 5 by the decay curve marked RNN.

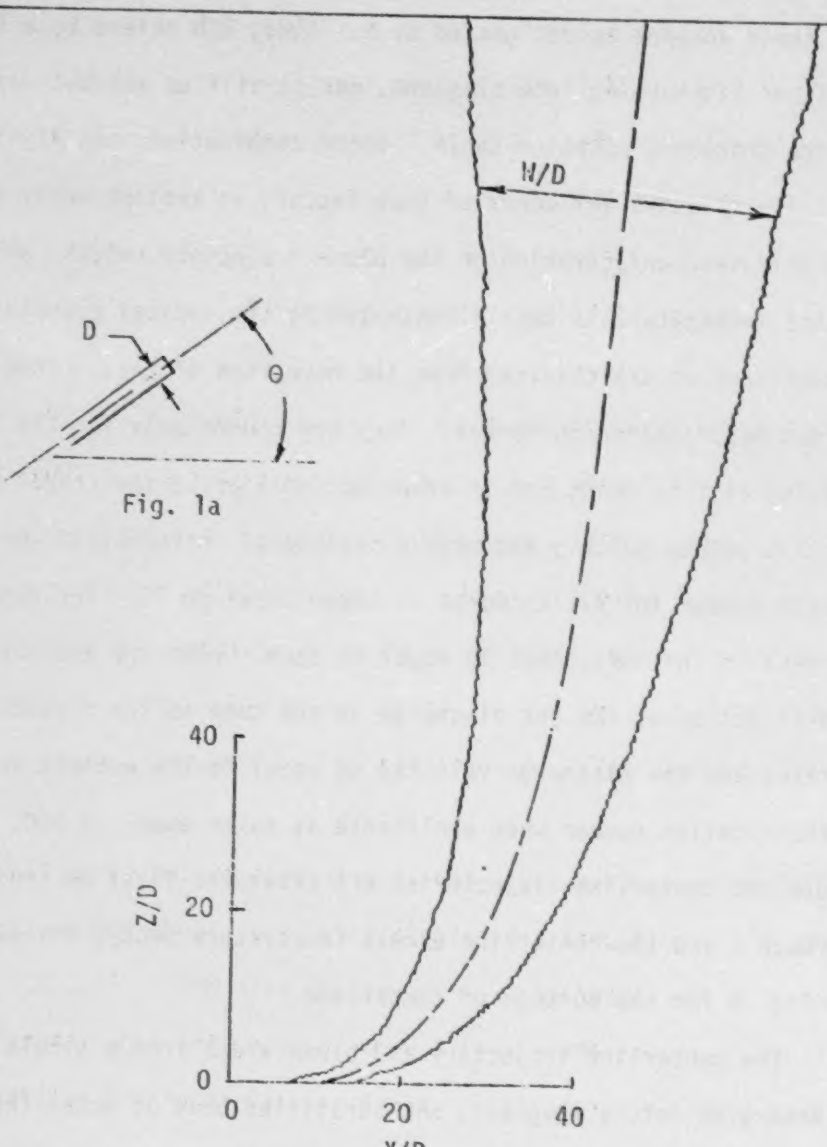
W/D
D
Θ
40
20
0
Z/D
0
20
40
X/D

Fig. 1a

Fig. 1b

Fig. 1 (a) A Single Round Port Diffuser at an Arbitrary Angle Θ, and (b) the Trajectory and Width of a Single Port Plume for Θ = 0° and F = 10 in a Non-Stratified, Stagnant Large Body of Water (RNN)

The centerline trajectory and plume width from a multiple port diffuser is plotted in Fig. 2; the ambient water is at rest and is non-stratified (MNN). Each port is equivalent to the single port discharge shown in Fig. 1. Comparison with this figure shows that the plume from a multiple port diffuser is wider and the trajectory less steep. The reason for this difference in plume behavior is the interference between the neighboring plumes in a multiple port discharge. For a short distance from the discharge point, individual round plumes issue from each port and maintain a trajectory identical to that in Fig. 1. The single round plume entrains ambient water from all sides and grows radially as it moves upward. After merging together with the neighboring plume to form a long rectangular source, the ambient water is entrained only from the sides and thus the plume is restricted to growth in only two directions. The multiple port plume also fails to penetrate the ambient water as much as a single round plume.

The consequence of plume interference on the centerline temperature along a multiple port plume trajectory is a slower temperature decay as seen from the comparisons of curves RNN with MNN in Fig. 5. It should be noted that this example, while demonstrating the dynamics of plume behavior, does not properly reflect the practical advantages of multiple port diffusers. In a typical situation when multiple port diffusers are used, the discharge from each port is only a small fraction of the total discharge from a single round diffuser so that dilution with distance from a multiple port diffuser can be substantially greater than at the same distance from an equivalent single port diffuser.

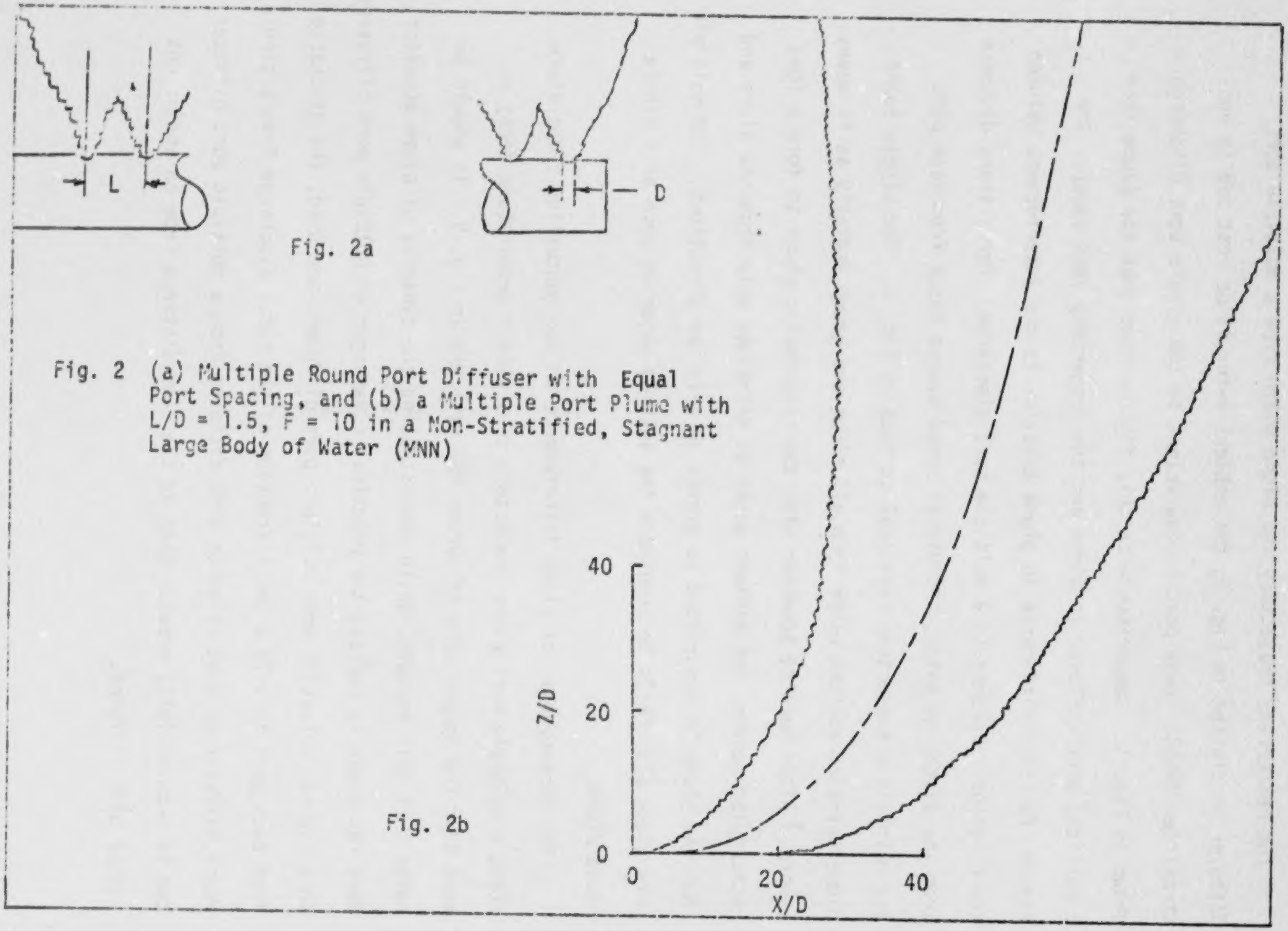

Fig. 2a

Fig. 2b

Fig. 2 (a) Multiple Round Port Diffuser with Equal Port Spacing, and (b) a Multiple Port Plume with $L/D = 1.5$, $\bar{F} = 10$ in a Non-Stratified, Stagnant Large Body of Water (MNN)

The plume trajectories for the two cases examined continue to rise as discussed earlier because the environment is non-stratified. Within a stratified environment, the plume trajectory may terminate as shown in Fig. 3 and often descends slightly from that height due to entrainment of cooler ambient water from lower depths. The plume trajectory and width plotted in this figure are for a single round port diffuser (RNS). By comparison with Fig. 1, the plume trajectory is less steep and the plume growth is substantially greater. The centerline plume temperature relative to the ambient decays at a considerably greater rate. This is seen from the comparison of curves marked RNN and RNS as well as MNN and MNS plotted in Fig. 5.

The effects of ambient current on plume characteristics are demonstrated by the plot of trajectory and width for a single port diffuser in moving, non-stratified water (RCN) in Fig. 4 and by the temperature decay curve RCN for the same diffuser as plotted in Fig. 5. The ambient current carries the plume downstream before it has a chance to spread. In the same time it exposes the plume to a greater ambient turbulence resulting in a substantial dilution.

Recall that the foregoing examples were given for a Froude number equal to 10 and for a fixed jet to ambient velocity ratio and stratification number. The numerous nomograms presented in this volume bring out the interrelationships between the discharge angle, discharge Froude number, ambient current, and stratification for single and multiple port diffusers. It should be pointed out that effects of such boundary conditions as ocean or river floor, free surface or confining walls and structures are totally excluded in all but Section VI. Sections II through VI are devoted to the discussion

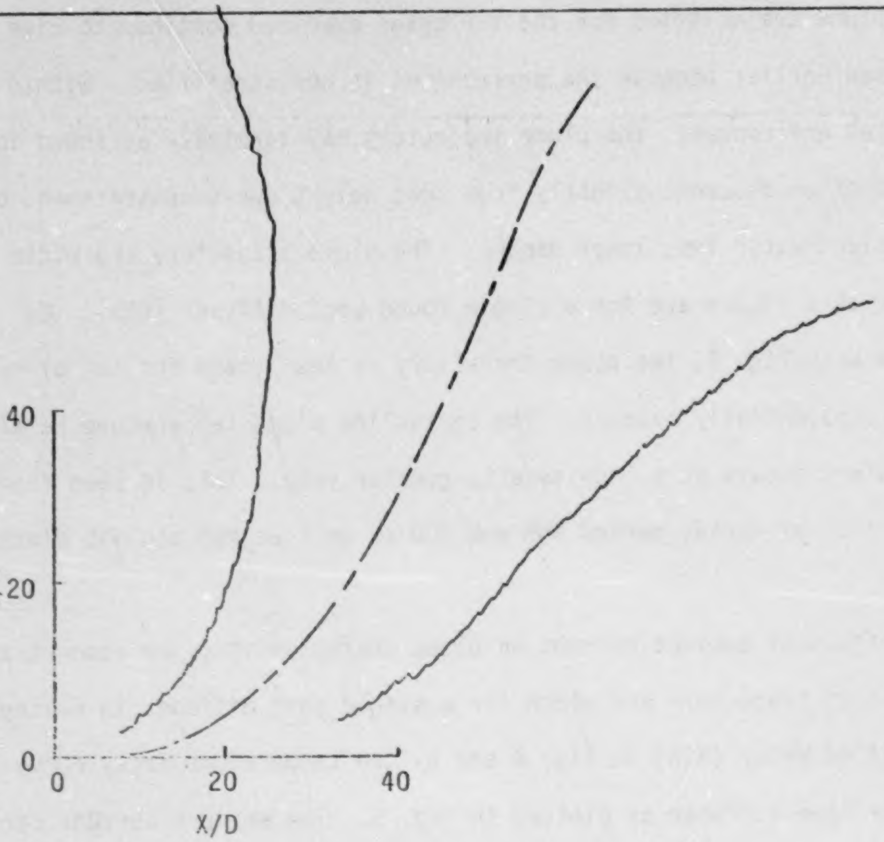

Fig. 3 Single Port Plume Trajectory and Width in a Stratified, Stagnant Large Body of Water: Θ = 0°, F = 10, S_t = 500 (RNS)

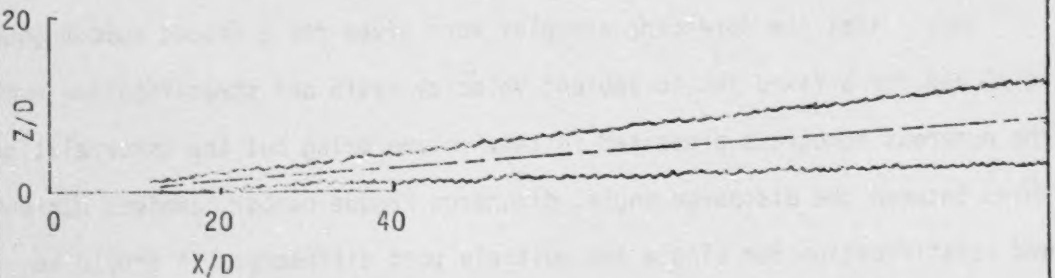

Fig. 4 Single Plume Trajectory and Width in a Non-Stratified, Moving Body of Water: Θ = 0°, F = 10 k = 1.0 (RCN)

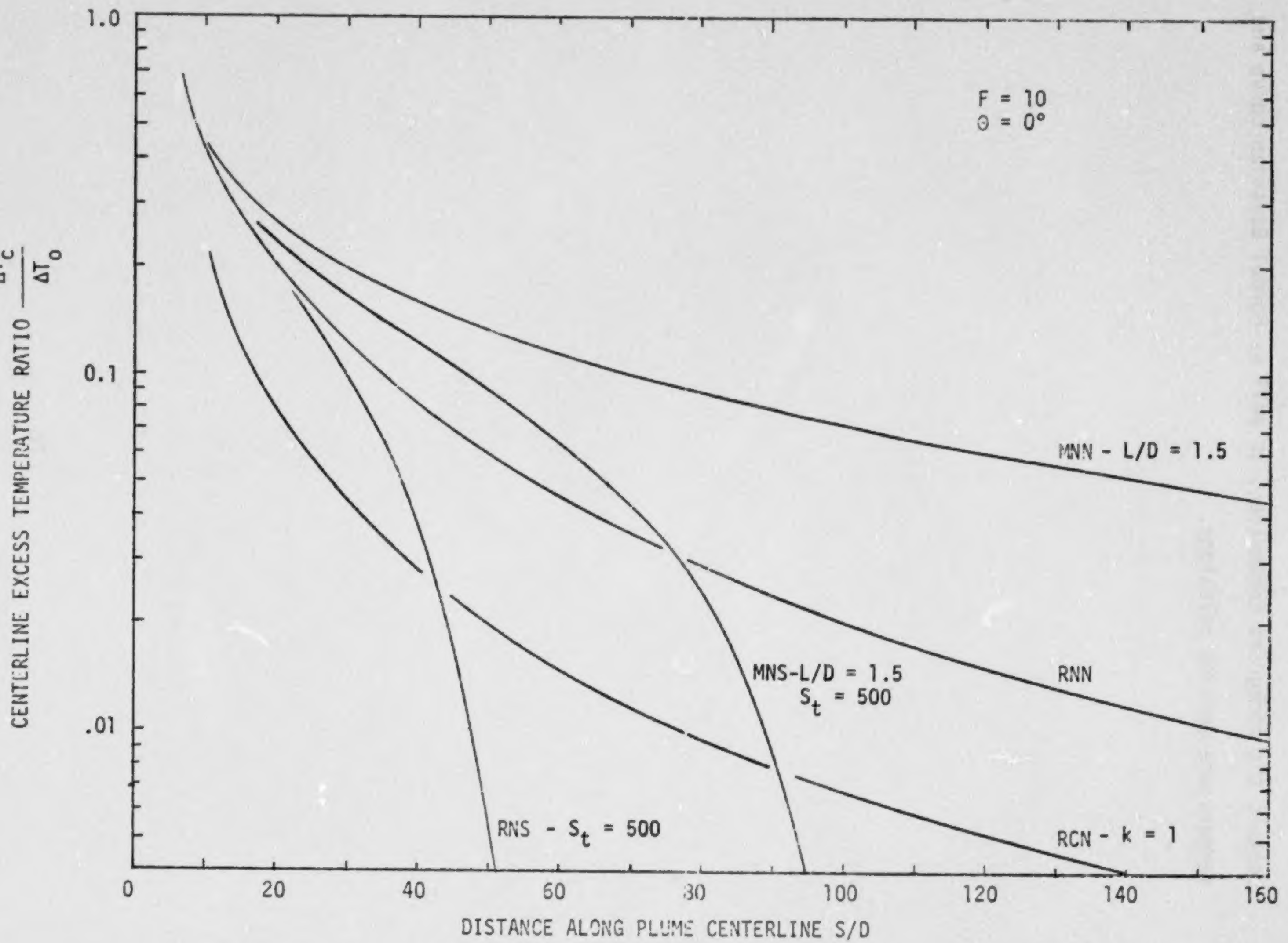

Fig. 5 Temperature Decay Curves for Various Diffuser Configurations and Ambient Water Conditions

and presentation of the nomograms. Section VII is devoted exclusively to illustrative examples for the use of the nomograms. The appendices contain the nomograms themselves, as well as normal Gaussian curve and temperature-density relations.

II. DISCHARGE INTO STAGNANT, NON-STRATIFIED WATER

The nomograms developed for this idealized situation are presented in Appendix A. The 14 cases considered in examples 1 through 4 (Section VII) illustrate the use of these nomograms. A description of the nomograms and basic assumptions underlying their development are presented below.

A. GENERALIZED NOMOGRAMS

Figures A-1 through A-35 of Appendix A are generalized nomograms developed for a discharge from a single port or a multiple port diffuser into a stagnant, non-stratified large body of water. The figure numbers corresponding to four different discharge angles and four diffuser port spacings are listed in Table I for easy reference.

The centerline trajectories of the heated plume are plotted with respect to the horizontal (X/D) and vertical (Z/D) space coordinates for discharge Froude numbers (F) ranging from 1 to 600. For a 90-degree discharge angle, the centerline trajectory is along the vertical space coordinate only and thus the excess temperature decay lines are given with respect to that coordinate alone. Superimposed on these curves are constant width lines that vary with discharge Froude number and the vertical space coordinate. For discharge angles other than 90 degrees, two identical centerline trajectory nomograms are given. Superimposed on the first are the constant excess centerline temperature lines and on the second the constant plume width lines.

All trajectory lines are dash-marked. The spacing between the asterisks on the centerline trajectories is equal to 20 diameters.

TABLE I

Figure Numbers Corresponding to Plume Behavior From Submerged Diffusers Discharging into Stagnant, Non-Stratified Water

Diffuser		Discharge Angle			
		0°	30°	60°	90°
RNN Single Jet		A-1,2	A-3,4	A-5,6	A-7
MNN Multiple Jet Diffuser	L/D = 1.5	A-8,9	A-10,11	A-12,13	A-14
	L/D = 10	A-15,16	A-17,18	A-19,20	A-21
	L/D = 20	A-22,23	A-24,25	A-26,27	A-28
	L/D = 30	A-29,30	A-31,32	A-33,34	A-35

B. BASIC ASSUMPTIONS

The nomograms have been developed from the governing mass, momentum, and energy equations as applied to a buoyant thermal plume. The solutions have been obtained after applying the well known integral method to the differential equations. Detailed derivations, assumptions, and computer programs are given in Reference 1 and are not repeated here.

Briefly, the integral technique requires that the velocity, temperature, and density profiles within the heated plume be specified so that these quantities can be integrated over the plume cross-section. It also requires that after a short developing distance the profiles maintain their form throughout the trajectory of the plume. Numerous laboratory experiments have demonstrated that the velocity profile is normally distributed near the discharge point. Similarly, temperature distribution measurements in the heated plume demonstrate that the temperature and density profiles are also normally distributed.

The temperature profile within the plume of a round jet is locally flatter than velocity profile. The degree of the relative spread of the temperature and density profiles as compared with the velocity profile is reflected in a constant turbulent Schmidt number taken equal to 1.16 in this study.

In the analysis, ambient turbulence is assumed not to contribute directly to dilution. It is assumed further that the rate of entrainment of the ambient fluid entering the plume radially is proportional to the local centerline velocity and hence the incremental rate of volume flow through the plume cross-section. The proportionality constant commonly known as the entrainment coefficient is assumed equal to 8.2 percent for the entire plume trajectory for a round jet.

The analysis of Reference 1 assumes that the initial development region between the source and the point where Gaussian profiles may be used is about 6.2 diameters downstream. It is further assumed that buoyant forces in this region are negligible. These assumptions are good for Froude numbers above about 10 but at lower Froude numbers the development length becomes less and the initial deflection due to buoyancy becomes apparent. The curves presented in this section include modifications to the development length for Froude numbers less than 10 as determined from Reference 2. This modification was applied uniformly to all discharge angles even though Reference 2 was developed specifically for the horizontal angle of discharge. The initial deflection angles for the stated Froude numbers were modified as suggested in the above reference for the horizontal discharge and by interpolation between zero and the vertical for 30 and 60 degree discharge angles.

Multiple diffusers are handled in the analysis of Reference 1 by considering the jets as round up to some transition region and as a slot after that. The transition point used in this work was where the entrainment of the round and slot jets were equal. This sudden transition from one solution to another results in a slight irregularity in temperature at the transition point.

The entrainment coefficient and turbulent Schmidt number used here for slot jet were .16 and 1.00, respectively. The sensitivity of the solution to the accuracy of turbulent Schmidt number and entrainment coefficient was tested by varying them plus and minus 10 percent from the values given above. It was found that varying the entrainment coefficient by 10 percent changed the position of the plume by about 2 percent;

the width and centerline temperature of the plume by about 10 percent. Varying the turbulent Schmidt number by 10 percent changed the location of the plume by about 5 percent, jet centerline excess temperature by about 10 percent, and plume width by about 1 percent.

III. DISCHARGE INTO STAGNANT, STRATIFIED WATER

The nomograms that were prepared for this situation are presented in Appendix B. Example 5 and example 6, cases 1 through 6, Section VII, illustrate the use of the nomograms. A description of the nomograms and basic assumptions underlying their development are presented below.

A. GENERALIZED NOMOGRAMS

Figures B-1 through B-48 of Appendix B are generalized nomograms developed for single port or multiple port diffusers discharging into a stagnant, stratified large body of water. The figure and identification numbers corresponding to four different discharge angles, three discharge elevations, and four diffuser port spacings are listed in Table II for easy reference.

When the ambient is stratified, several other variables come into play making it difficult to express solutions in the general form used for the non-stratified case. These variables are density and temperature profiles within the ambient and depth of discharge relative to the stratified region.

Most large bodies of water are stratified to some degree, and even weak stratification can have a profound effect on the plume behavior. As the plume rises in a stratified environment, it initially entrains cool water and carries it into warmer layers of water. The plume temperature continues to drop while the temperature of its surrounding continues to increase with elevation. Meanwhile, the plume decelerates due to the loss of buoyancy, but continues rising because of its excess momentum even when its centerline temperature at a point along its trajectory equals the local ambient temperature. This excess momentum

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TABLE II

Figure Numbers Corresponding to Plume Behavior From Submerged Diffusers Discharging into a Stagnant, Stratified Ambient Water

Diffuser	$Z_s/D = 0$				$Z_s/D = 10$				$Z_s/D = 30$			
	$\Theta=0°$	$\Theta=30°$	$\Theta=60°$	$\Theta=90°$	$\Theta=0°$	$\Theta=30°$	$\Theta=60°$	$\Theta=90°$	$\Theta=0°$	$\Theta=30°$	$\Theta=60°$	$\Theta=90°$
RNS	B- 1	B- 2	B- 3	B- 4	B- 5	B- 6	B- 7	B- 8	B-9	B-10	B-11	B-12
MNS L/D=1.5	B-13	B-14	B-15	B-16	B-17	B-18	B-19	B-20	B-21	B-22	B-23	B-24
MNS L/D=10	B-25	B-26	B-27	B-28	B-29	B-30	B-31	B-32	B-33	B-34	B-35	B-36
MNS L/D=20	B-37	B-38	B-39	B-40	B-41	B-42	B-43	B-44	B-45	B-46	B-47	B-48

carries the plume from this point to its terminal height; i.e., the maximum height of rise, while the centerline temperature continues to drop below the local ambient temperature.

The parameter, $S_t = \frac{\Delta\rho_o/D}{\Delta\rho_a/\Delta Z}$ may be used as a correlation parameter for stratification, where $\Delta\rho_o/D$ is the difference in density between the initial jet and the ambient divided by jet diameter and $\Delta\rho_a/\Delta Z$ is the local ambient density gradient. If the coefficient of volumetric expansion is assumed constant, this parameter can be written as $S_t = \frac{\Delta T_o/D}{\Delta T_a/\Delta Z}$. Table F-1 in Appendix F provides relationships between the ocean water density and temperature for several salinity levels. This table may be used for estimating S_t.

Although the computer program developed in Reference 1 can handle any arbitrary stratification profile, it is not practical to consider all possible cases here. Many profiles can be approximated, however, by the combination of a non-stratified region and a linearly stratified region as shown in Fig. 6.

For the sample case shown on Fig. 6, the natural water density stratification is shown as a solid line. Water density is constant from the bottom to a depth of Z = 20 ft. above the bottom. From this point all the way to the water surface the ambient water density decreases non-linearly as indicated. The discharge is assumed to take place at Z = 10 ft. from the bottom. In order to use the nomograms for the analysis of plume characteristics we must: (1) linearize the natural density curve by drawing a best straight line through it, (2) find the slope of this line for the calculation of S_t, and (3) estimate Z_s which is the depth of the non-stratified water above the discharge point that results in the

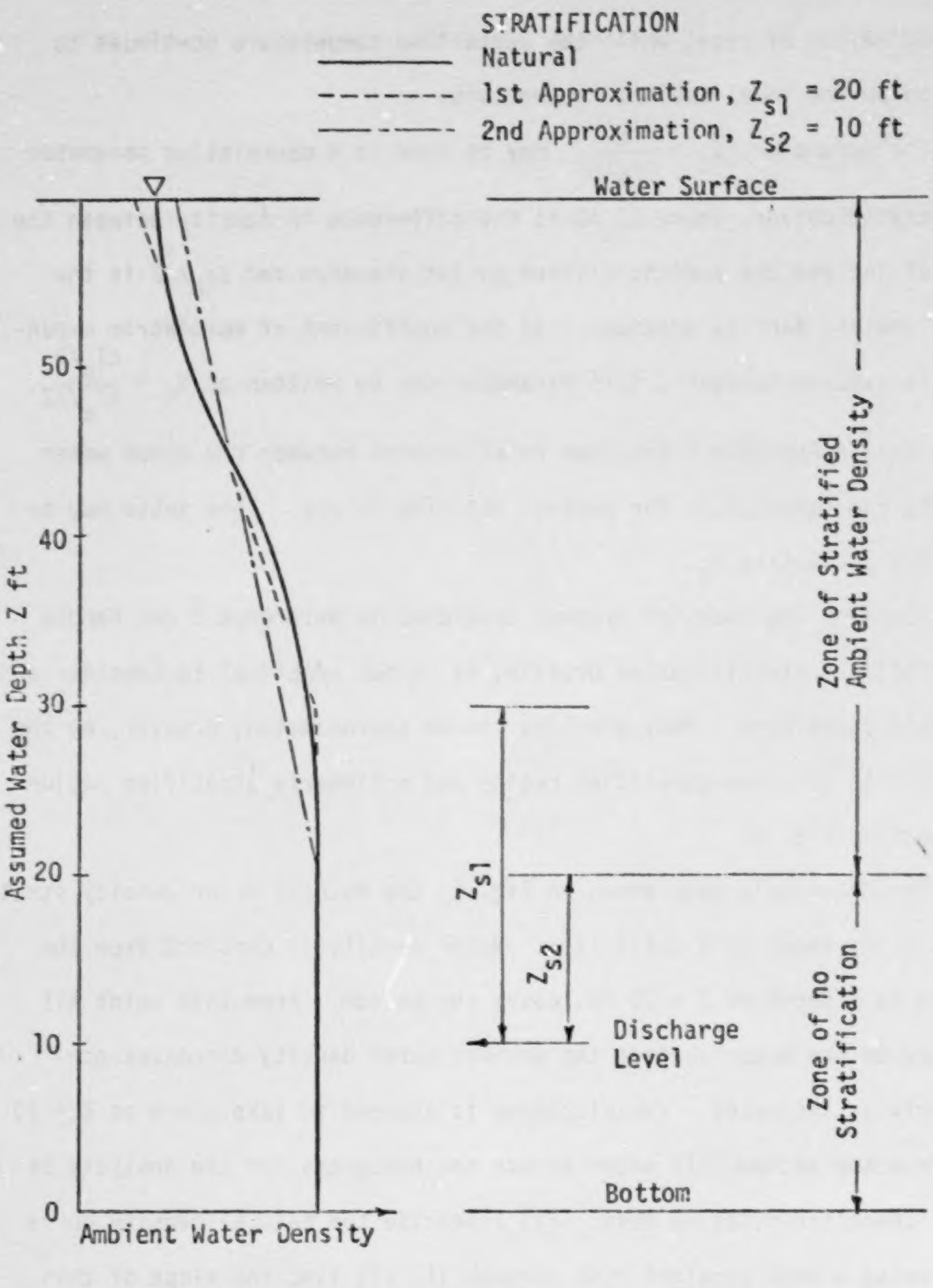
STRATIFICATION
Natural
1st Approximation, Z_{s1} = 20 ft
2nd Approximation, Z_{s2} = 10 ft
Water Surface
Assumed Water Depth Z ft
50
40
30
20
10
0
Ambient Water Density
Z_{s1}
Z_{s2}
Discharge Level
Bottom
Zone of Stratified Ambient Water Density
Zone of no Stratification

Fig. 6 Linearization of the Natural Density Stratification and the Definition of Z_s

process of linearization. It is best to try more than one way to linearize the density curve so that a range of possible solutions is obtained. Two such approximations are indicated in Fig. 6 leading to values of Z_{s_1} and Z_{s_2} for the first and second approximations, respectively.

The nomograms are presented for several values of Z_s and several slopes. Both parameters are expressed in dimensionless numbers. They are Z_s/D and the stratification number S_t, respectively. In this report values of Z_s/D = 0, 10 and 30 and S_t = 100, 500, 1000, and 2500 have been considered.

Since it is not possible to present complete temperature-trajectory solutions for all combinations, the results for discharge angles of 0, 30, and 60 degrees are presented as follows: For each Froude number and stratification parameter a trajectory is given which is terminated at the point of maximum rise. Since the plume centerline temperature varies with Froude number as well as with stratification number, and since four values of each parameter are presented in a single nomogram, constant temperature lines similar to those for non-stratified case (Appendix A) cannot all be drawn without causing the chart to become overly complex. Only the 5 percent temperature lines, that is $\frac{\Delta T_c}{\Delta T_o} = .05$, are drawn and appropriately marked for the S_t they represent. Additional information on temperature is provided by plus (+) marks on each trajectory to show the plume centerline coordinate where the excess temperature above ambient becomes zero, that is where $\frac{\Delta T_c}{\Delta T_o} = 0$. In order to obtain an idea of the temperature decay along the plume in a typical situation, the reader should refer to Figure 5.

For a 90-degree discharge angle where the trajectory is vertical, curves are presented giving the terminal height and the 5 percent excess temperature point as functions of Froude number with S_t as a parameter.

B. BASIC ASSUMPTIONS

The nomograms for this case have been prepared from the solution of the same set of equations discussed in Section III-B and Reference 1. All basic assumptions of that section apply here as well. The only exception is that the ambient water is assumed stratified with respect to density. This stratification is assumed to be linear and could be the result of temperature or salinity variations with depth.

It should be repeated here that the restriction just discussed is imposed to facilitate presentation of generalized nomograms. It is not a basic limitation. The computer program of Reference 1 allows for arbitrary density as well as temperature profiles in the ambient water.

IV. DISCHARGE INTO MOVING, NON-STRATIFIED WATER

The nomograms for discharge into moving, non-stratified ambient water are presented in Appendix C. The 11 cases considered in examples 7, 8, and 9 (Section VII) illustrate the use of the nomograms. A description of the nomograms and the basic assumptions underlying their development are presented below.

A. GENERALIZED NOMOGRAMS

Figures C-1 through C-30 of Appendix C are generalized nomograms developed for a single port diffuser discharging into moving, non-stratified ambient water. The figure numbers corresponding to four different discharge angles (θ) and a wide range of velocity ratios (k) are listed in Table III for easy reference.

The discharge angles are referenced with respect to the horizontal space coordinate, thus at zero discharge angle, the jet discharge and ambient current are in the same direction. At a 90-degree discharge angle, the jet discharge is vertical and perpendicular to the direction of the ambient current.

The centerline trajectories of the heated plume are plotted with respect to horizontal (X/D) and vertical (Z/D) space coordinates for selected discharge Froude numbers. Superimposed on the centerline trajectories are the excess centerline temperature lines and constant plume width lines, each on a separate chart for a given velocity ratio.

The limited range of Froude numbers and velocity ratios presented reflect the scarcity of data with ambient current. The absence of generalized nomograms for multiple diffusers (MCN) is also evidence of a lack of appropriate data.

TABLE III

Figure Numbers Corresponding to Plume Behavior From Single Port Submerged Diffusers Discharging into Moving, Non-Stratified Water

k	Discharge Angle			
	Co-flow $\Theta=0^\circ$	Cross-flow $\Theta=90^\circ$	$\Theta=30^\circ$	$\Theta=60^\circ$
0.5	C-1,2			
1	C-3,4			
2	C-5,6	C-19,20	C-11,12	C-15,16
4	C-7,8	C-21,22	C-13,14	C-17,18
6	C-9,10	C-23,24		
8		C-25,26		
12		C-27,28		
16		C-29,30		

The reader is urged to carefully study the basic assumptions that follow before attempting to use the nomograms.

B. BASIC ASSUMPTIONS

The nomograms in this set have been drawn from three different sources and thus are subject to different limitations. However, they are all limited to uniform velocities in the ambient current. The three sources are: Reference 3 for co-flow ($\theta = 0°$) data, Reference 4 for the cross-flow ($\theta = 90°$) data, and References 5 and 6 for the analysis of the remaining (i.e., 30 and 60 degree) nomograms.

The co-flow data obtained from Reference 3 are from a comprehensive set of experiments with heated and salt water jets performed in a turbulent channel flow. The discharge Froude number and the jet to ambient velocity ratio (k) were varied among a wide range of values shown by the solid line in Fig. 7. Empirical equations developed by correlating the experimental data were derived for plume width, centerline temperature and plume trajectory. The correlations were used in the preparation of the nomograms for a range of parameter space both inside and outside the experimental range. The dashed line in Fig. 7 show the extent of extrapolation.

Reference 4 presents a comprehensive set of cross-flow ($\theta = 90°$) data obtained in laboratory experiments. A wide range of discharge Froude numbers and jet to ambient velocity ratios (k) were tested. The range of parameter space for k and Froude number are plotted in Fig. 8 as indicated by the solid line. The data from these experiments were correlated to form expressions for the centerline temperature, the plume width and the plume rise. The correlations were used in the preparation

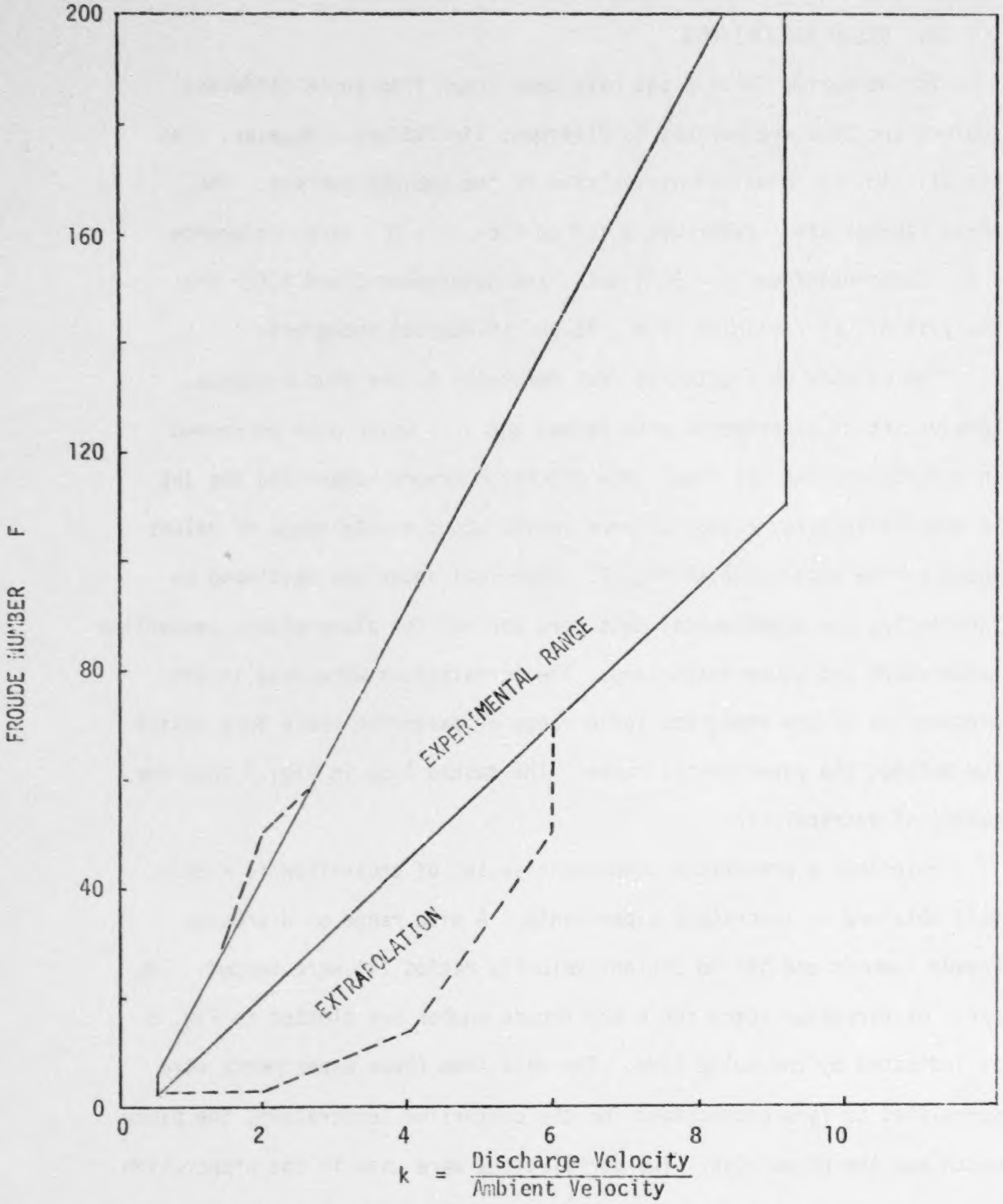

Fig. 7 The Range of Experimental Parameters and the Extent of Extrapolation Reported in this Volume for Co-flow Data

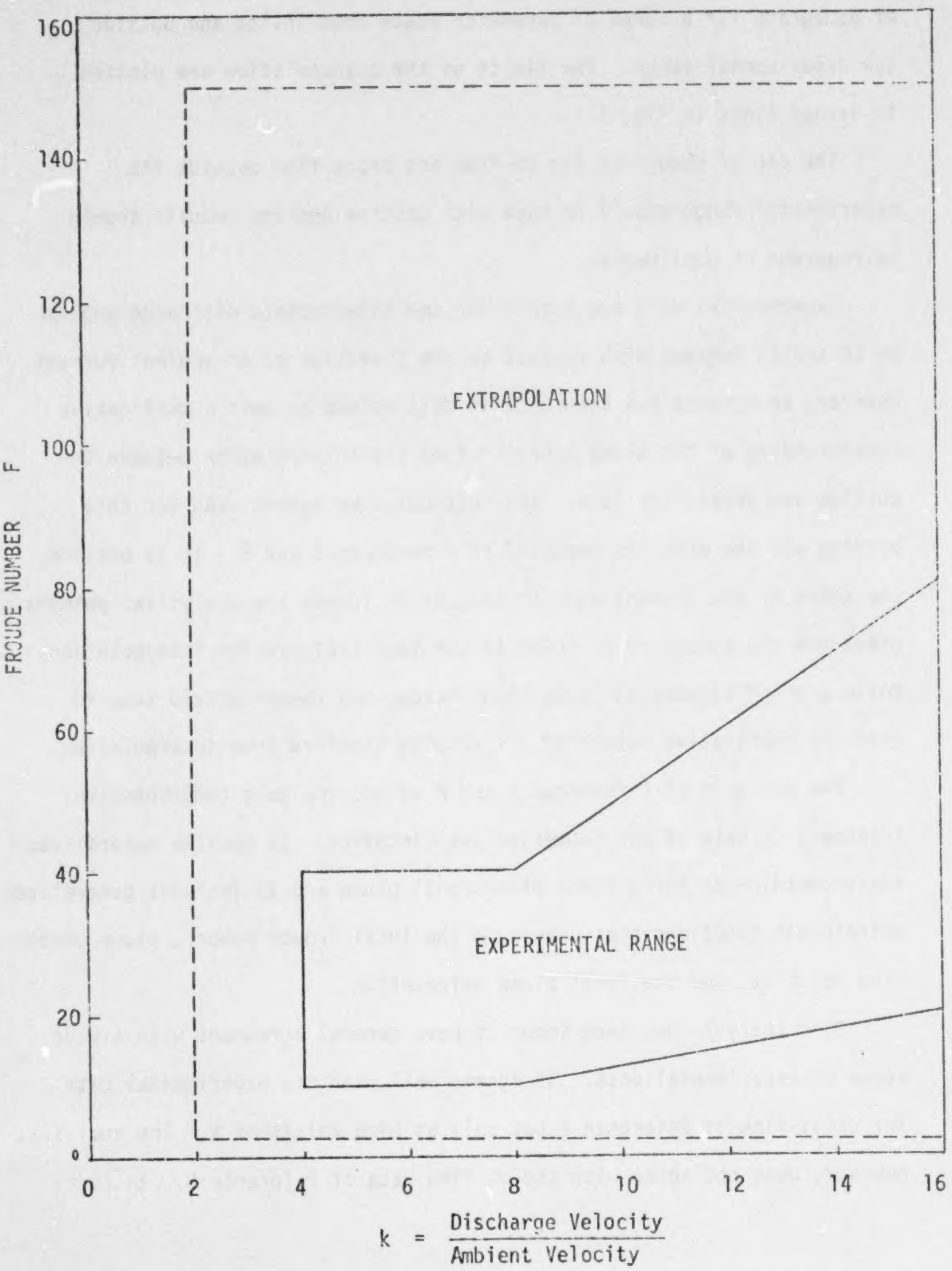

Fig. 8 The Range of Experimental Parameters and the Extent of Extrapolation Reported in this Volume for Cross-flow Data

of nomograms for a range of parameter space both inside and outside the experimental range. The limits of the extrapolation are plotted in dashed lines in Fig. 8.

The use of nomograms for co-flow and cross-flow outside the experimental range should be made with caution and the results should be regarded as qualitative.

Experimental data are scarce for the intermediate discharge angles of 30 and 60 degrees with respect to the direction of an ambient current. However, an attempt has been made in this volume to gain a qualitative understanding of the plume behavior from the interpolation between the co-flow and cross-flow data. The interpolation scheme used for this purpose was the analysis reported in References 5 and 6. It is outside the scope of the present work to discuss at length the analytical methods cited and the procedure followed to use such analysis for interpolation. While a brief discussion is outlined below, the reader should keep in mind the qualitative nature of all results obtained from interpolation.

The analysis of References 5 and 6 offers the most comprehensive treatment to date of the submerged jet discharge. It handles generalized space coordinates for a three dimensional plume and it includes generalized entrainment functions that depend on the local Froude number, plume centerline velocity, and the local plume orientation.

This analysis has been shown to have general agreement with a wide range of experimental data. It agrees well with the experimental data for cross-flow of Reference 4 but only at high values of k. The analysis, however, does not agree with the co-flow data of Reference 3. In fact

, it even fails to predict the proper qualitative trend of the plume behavior with respect to k and Froude number for co-flow discharge. Consequently, the analysis of Reference 5 and 6 cannot be used directly for predicting the plume behavior for the intermediate angles of 30 and 60 degrees.

The approach used herein was to force the analysis of References 5 and 6 to agree with data for co-flow discharge as closely as possible without disrupting the acceptable qualitative agreement it is already capable of with respect to cross-flow discharge. Once this was accomplished satisfactorily, the analytical model was used to predict the plume behavior between the co-flow and cross-flow discharge angles of 30 and 60 degrees. In other words, the analytical model now was used as a powerful interpolating scheme between two sets of experimental data.

It should be of interest to some readers to know that the analysis of References 5 and 6 was fitted to the experimental data of Reference 3 by manipulating the ambient turbulence terms that were originally neglected in those calculations. This points to an intellectually curious subject, namely; that the ambient turbulence terms while not affecting the cross-flow prediction, does affect and indeed improve the co-flow prediction in the analysis of References 5 and 6. This observation has been verified experimentally in the cross-flow analysis of Reference 4 and the recent co-flow data of Reference 3, respectively.

There is no published comprehensive analysis of the multiple jet diffuser system with ambient current. The available data are scattered and fragmentary. It is noted, however, that the behavior of a multiple port diffuser up to the point of plume interaction can be obtained from the analysis of a single port. This is demonstrated in examples 7 and 9 of Section VII.

V. DISCHARGE INTO MOVING, STRATIFIED WATER

The nomograms for discharge into moving, stratified ambient water is presented in Appendix D. Example 10, cases 1 through 6, of Section VII, illustrate the use of the nomograms. A description of the nomograms and the basic assumptions underlying their development are presented below.

A. GENERALIZED NOMOGRAMS

Figures D-1 through D-16 of Appendix D are generalized nomograms developed for single port diffusers discharging at 0, 30, 60, and 90 degrees into moving and stratified ambient water. The figure numbers corresponding to two different jet to ambient velocity ratios and two ambient stratification numbers are listed in Table IV for easy reference.

The discharge angles are referenced with respect to the horizontal space coordinate so that at zero degree discharge angle, the jet discharge and the ambient current are in the same direction. At 90 degrees discharge angle the jet is perpendicular to the direction of the ambient current.

The nomograms are presented in pairs, giving the temperature chart and the width chart on consecutive figures. For each discharge angle, the centerline trajectory of the plume is plotted with respect to the horizontal and vertical space coordinates. If the maximum height of rise occurs at less than 200 diameters downstream of the discharge, it is marked by a cross in the nomogram, and the trajectory is terminated.

Superimposed over the centerline trajectories are the constant centerline excess temperatures and constant width lines. If the plume

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TABLE IV

Figure Numbers Corresponding to Plume Behavior for Diffuser Discharging into Moving and Stratified Ambient Water

S_t	k = 2		k = 4	
	F = 10	F = 30	F = 30	F = 75
100	D-1,2	D-3,4	D-5,6	D-7,8
500	D-9,10	D-11,12	D-13,14	D-15,16

has entrained enough cool waters from the lower elevations so that its centerline temperature is less than the local ambient temperature, then an appropriate negative excess temperature is designated.

The limited range of Froude numbers, stratification numbers, and velocity ratios reflect the uncertainty in these data due to lack of adequate experimental verification. The reader is urged to study the basic assumptions that follow before attempting to use the data.

B. BASIC ASSUMPTIONS

All nomograms presented in this section were obtained analytically from the modified programs of References 5 and 6 and thus are subject to all limitations discussed in Section IV-B concerning the intermediate injection angles of 30 and 60 degrees. Unlike the development of Section IV where comprehensive experimental data for co-flow and cross-flow were available and were used to interpolate for 30 and 60 degrees, such data for stratified cases are scarce indeed and thus all nomograms of this section should be used with caution.

VI. VERTICAL DISCHARGE INTO NON-STRATIFIED STAGNANT SHALLOW WATER (A SPECIAL CASE OF RNN)

The nomograms for the discharge into a non-stratified, stagnant, shallow body of water is presented in Appendix E. The four cases considered in example 11 of Section VII illustrate the use of the nomograms.

A. GENERALIZED NOMOGRAMS

Figures E-1 through E-6 of Appendix E are nomograms developed for a single port diffuser discharging vertically upward into a shallow body of water. Only a selected number of discharge conditions and Froude numbers are presented. The corresponding figure numbers of these cases are listed in Table V. Nomograms are given for the following types of information: (1) the centerline excess temperature in relation to the ambient from the discharge point to the water surface, (2) surface water temperature directly above the diffuser at the center of the boil and along concentric circles around this point, and (3) isotherms throughout the plume.

The discharge depth enters these calculations as a new parameter and it strongly affects the results. No attempt has been made at this time to include this parameter in a unifying correlation function, nor has an effort been made to cover a wide range of discharge conditions and ambient stratification.

B. BASIC ASSUMPTIONS

A generalized submerged plume program that adequately analyzes the combined subsurface transition and the surface spreading zones of the plume is not yet available. The nomograms of this section are the results

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TABLE V

Figure Numbers Corresponding to Plume Behavior for a Single Port Diffuser Discharging Vertically Upward into Non-Stratified, Stagnant, Shallow Body of Water

Discharge Depth Z/D	F = 1, 5, 25, 100		Isotherms	
	Centerline Temperature	Surface Temperature	F = 45	F = 51
5	E-3			E-6
8.4			E-5	
10	E-2	E-4		
40	E-1			

of an analysis of the transition zone of the submerged plume as it reaches the water surface. The analysis is specifically suitable for evaluating the plume behavior from a very large diffuser discharging vertically in shallow water. This is a situation where effects of water surface become important and analyses of previous sections become invalid. This is particularly true when submergence is on the order of 10 diameters or less. Since numerous examples of this type of diffuser are found among coastal power plant discharges, a special consideration of the problem is in order.

The model for shallow discharge used here was developed for EPA and is described in Reference 7. It consists of a finite difference solution of a two-dimensional axisymmetric plume in ambient water that is at rest. Like many mathematical models of fluid flow phenomena, this model requires information on the turbulence characteristics of the flow field and the results are altered for various assumptions made on that input. It suffices to state, however, that as a consequence of the input variables used in this model reasonable predictions are obtained.

VII. EXAMPLE PROBLEMS

Numerous examples are given in this section to familiarize the reader with the use of the nomograms. Even though an attempt was made to develop more or less realistic problem statements, the examples should not be construed as representing a preferred design or recommended temperature zone. The numbers in these examples have been conveniently rounded off.

Example Problem 1

Given:

A 500 MW nuclear power plant is located on a open coastline. A single port submerged diffuser is used to discharge the condenser cooling water into the ocean. The following design data apply:

a. Waste heat to cooling water = 3.2×10^9 Btu/hr

b. Condenser ΔT (ΔT_o) = 20° F

c. Discharge angle $\theta = 0.0°$

d. Discharge velocity U_j = 10 ft/sec

e. Ambient water is stagnant and non-stratified (RNN), T_a = 50° F and salinity = 25 ppt

f. Discharge depth Z_o = 200 ft

Determine:

1. The location of the plume where the centerline temperature is 2° F above the ambient (i.e., 52°).

2. The centerline temperature and plume width when the plume reaches the surface.

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Solution:

Part 1

The discharge Froude number is obtained first from the above information as follows:

$$Q = H_c/(\rho c \Delta T_o) = \frac{3.2 \times 10^9 \text{ Btu/hr}}{(64 \text{ lb/ft}^3)(1.0 \text{ Btu/lb-°F})(20°\text{F})(3600 \text{ sec/hr})}$$

$$Q = 700 \text{ ft}^3/\text{sec}$$

$$A = Q/U_j = \frac{700 \text{ ft}^3/\text{sec}}{10 \text{ ft/sec}} = 70 \text{ ft}^2$$

$$D = (4A/\pi)^{1/2} = (4 \times 70/3.14)^{1/2} = 9.5 \text{ ft}$$

where Q is the volumetric flow rate of water and U_j is the discharge velocity in cfs and fps respectively, H_c is the waste heat load in Btu/hr, ρ is the water density, c is the heat capacity of water usually taken as unity and ΔT_o is the initial temperature difference, or the condenser ΔT.

The Froude number equals $U_j/(\frac{\Delta\rho_o}{\rho_o} gD)^{1/2}$, where $(\frac{\Delta\rho_o}{\rho_o} g)^{-1/2} = G \simeq 3.7$ is obtained from Fig. F-1 in Appendix F for S = 25 ppt, $T_a = 50°$ F and $\Delta T_o = 20°$ F.

Thus, $F = GU_j D^{-1/2} = 3.7 \times 10 \times (9.5)^{-1/2}$

$F = 12$

For a single port diffuser discharging into stagnant, non-stratified water (RNN) with a discharge angle of zero with respect to the horizontal, use nomogram A-1 to find location of the plume where the centerline temperature is 2° F above ambient.

The centerline excess temperature ratio corresponding to 2° F is,

$$\frac{\Delta T_c}{\Delta T_o} = 2/20 = 0.1$$

Entering Fig. A-1 at F = 12 and $\frac{\Delta T_c}{\Delta T_o} = 0.1$, the location of the plume centerline is found to be

$$X/D \simeq 29 \text{ and } Z/D \simeq 15$$

Therefore, since D = 9.5 ft,

$$X \simeq 275 \text{ ft and } Z \simeq 142 \text{ ft (answer to Part 1)}$$

Part 2

Since the discharge depth is 200 ft and D = 9.5 ft, water surface is reached when $Z_o/D = 200/9.5 \simeq 21$.

Fig. A-1 at Z/D = 21 and F = 12 gives a value of $\frac{\Delta T_c}{\Delta T_o}$ of about 0.08 at the surface. Therefore, the centerline excess temperature as it reaches the surface is 50 + 1.6 = 51.6° F.

Entering Fig. A-2 at Z/D = 21 and F - 12, the value of W/D is found to be about 15. Thus, the plume width at the surface is 15 x 9.5 ≃ 142 ft.

It should be noted the nomograms, except Appendix E, exclude the effect of surface interference. Thus, surface temperatures calculated from these nomograms in this and other examples are underestimated.

Example Problem 2

Given:

A 1000 MW nuclear power plant is located on an open coastline. A submerged single port diffuser is used to discharge the condenser cooling water. The following design data apply:

a. Waste heat to cooling water = 6.4×10^9 Btu/hr

b. Condenser ΔT (ΔT_o) = 20° F

c. Discharge angle $\theta = 30°$

d. Discharge velocity U_j = 10 ft/sec

e. Ambient water is stagnant and non-stratified, T_a = 50° F and salinity = 25 ppt

f. Discharge depth Z_o = 150 ft

Determine:

1. The location of the plume when the centerline temperature is 2° F above ambient.

2. The centerline temperature and plume width when the plume reaches the surface.

Solution:

Part 1

The Froude number is calculated following the procedure of problem 1, i.e.,

$$Q = \frac{6.4 \times 10^9 \text{ Btu/hr}}{(64 \text{ lb/ft}^3)(1.0 \text{ Btu/lb-°F})(20° \text{ F})(3600 \text{ sec/hr})}$$

$$Q \simeq 1400 \text{ ft}^3\text{/sec}$$

$$A = \frac{1400 \text{ ft}^3\text{/sec}}{10 \text{ ft/sec}} = 140 \text{ ft}^2$$

$$D = (4 \times 140/3.14)^{1/2} = 13.3 \text{ ft}$$

$$F = 3.7 \times 10 \times (13.3)^{-1/2} \simeq 10$$

For a single port diffuser discharging into stagnant, non-stratified water (RNN) with a discharge angle $\theta = 30°$, use nomogram A-3 to find location of plume when centerline temperature is 2° F. Entering Fig. A-3 at $F = 10$ and $\frac{\Delta T_c}{\Delta T_o} = 2/20 = 0.1$, it is found that

$$X/D \simeq 20 \text{ and } Z/D \simeq 25$$

Since D = 13.3 ft, therefore

$$X \simeq 270 \text{ ft and } Z \simeq 330 \text{ ft}$$

Note that since the total depth (Z_0) is only 150 ft, the plume cannot extend to 330 ft above the discharge. Thus, the plume centerline temperature will exceed 2° F above the ambient at all points along its trajectory. If the ΔT_c were restricted to 2° F before or at the surface, other discharge configurations or discharge conditions than specified in this problem would be required.

Part 2

The plume centerline temperature at the surface is found from Fig. A-3 for F = 10 and $Z_0/D = 150/13.3 \simeq 11$. The percent excess temperature at this location is $\frac{\Delta T_c}{\Delta T_o} \simeq 0.25$. Therefore, $\Delta T_c = 0.25 \times 20 = 5°$ F giving a plume centerline temperature at the surface of 50 + 5 = 55° F.

The width of the plume is determined from Fig. A-4. Entering this figure with Z/D = 11 and F = 10, it is found that

$$W/D \simeq 6 \text{ or } W \simeq 6 \times 13.3 \simeq 80 \text{ ft}$$

Variations of Problem 2 for different discharge angles and discharge volume from a single diffuser have been solved to see if discharge conditions other than the single port at 30 degrees could meet the 2° F surface temperature difference requirement. The results for the above example and five additional cases examined are tabulated in Table VI. It is seen that case number 4 satisfies the above requirement. This case is for two ports each discharging 700 cfs horizontally. The ports are located far enough apart so that their plumes do not interact. This condition is satisfied if the spacing between ports is made greater than the predicted plume width at the water surface.

TABLE VI

Variations on Problem 2 Showing Several Discharge Conditions

Case		1	2	3	4	5	6
No. of Ports		1	1	1	2*	2*	2*
Port Diameter (ft)		13.3	13.3	13.3	9.5	9.5	9.5
Froude Number		10	10	10	12	12	12
Discharge Angle θ (degree)		30	0	90	0	30	90
Plume Location for	X(ft)	270	320	0	275	200	0
$\Delta T_c = 2°$ F	Z(ft)	330	230	430	142	230	300
T_c at Surface (°F)		5	2.4	8	1.9	3.2	6
Width at Surface (ft)		80	134	67	114	76	60
Figures Used		A-3,4	A-1,2	A-7	A-1,2	A-3,4	A-7
Conditions Met?		No	No	No	Yes	No	No

---

*The plumes from the two ports are assumed to be non-interacting.

Example Problem 3

Given:

a. Discharge Froude No. F = 15

b. Discharge angle $\theta = 60°$

c. Initial temperature difference $\Delta T_o = 20°$ F

d. Single port diffuser

e. The receiving water is stagnant and non-stratified (RNN)

Determine:

1. The location and width of the plume where the centerline temperature is 2° F above the ambient.

2. At this location, find the radial distance from the center of the plume to the point where the plume has a temperature which is 1° F warmer than the ambient.

Solutions

Part 1

For the dilution to a centerline excess temperature $\Delta T_c = 2°$ F, the dimensionless temperature ratio is $\frac{\Delta T_c}{\Delta T_o} = \frac{2}{20} = 0.1$. Using Fig. A-5 for RNN, a discharge angle (θ) of 60 degrees, a Froude Number F = 15, and a centerline excess temperature ratio $\frac{\Delta T_c}{\Delta T_o} = 0.1$, one obtains $X/D \simeq 14$ and $Z/D \simeq 30$. Using these trajectory values with Fig. A-6 gives $W/D \simeq 13$.

Part 2

In order to solve for the radial distance at this point in the trajectory to the 1° F excess temperature line, the Gaussian distribution curve given on Fig. F-2 is used. This figure presents the approximate radial temperature distribution within the plume as a fraction of the maximum excess temperature at the center. The radial parameter $\eta = 4r/W$, where r is the radial distance from the center of the plume and W is the local plume width (or diameter). T_r-T_a is the excess temperature within the plume which depends on the radius and T_c-T_a is the centerline excess temperature at this point in the trajectory. For this problem, $\frac{T_r - T_a}{T_c - T_a}$ = 1/2 = 0.5. At this value on Fig. F-2, the value of η is found to be 1.2. Using $\eta = 4r/W$ and W/D = 13 from Part 1 one finds the desired value of the radial distance from the center of the plume to be $r/D \simeq 1.2 \times 13/4 \simeq 4.5$.

The procedure in this example can be used to generalize all temperature and width nomograms presented in this volume. Namely, based on the centerline temperature data of nomograms and the Gaussion distribution curves of Fig. F-2, the temperature at an arbitrary radial distance in a plume cross-section can be found.

Example Problem 4

Given:

The problem statement is the same as given in Problem 2 except a multiple port diffuser is used that consists of a single row of 10 equal jets spaced 10 diameters apart, i.e., MNN with L/D = 10.

Solution:

Part 1

From Problem 2, the total volumetric flow rate and the total discharge area are $Q = 1400\ \text{ft}^3/\text{sec}$ and $A_{total} = 140\ \text{ft}^2$, respectively.

For ten equal ports, the discharge area per port and the single port diameter are:

$$A' = \frac{A_{total}}{\text{No. of ports}} = 140/10 = 14\ \text{ft}^2 \text{ per port}$$

$$D = (4 \times 14/3.14)^{1/2} = 4.2\ \text{ft}$$

With this information and for the values of G and U_j of Problem 2, the discharge Froude number becomes:

$$F = 3.7 \times 10 \times (4.2)^{-1/2} \simeq 18$$

The plume location when the centerline excess temperature is 2° F above ambient is obtained from Fig. A-17 for a multiple port diffuser with L/D = 10 and $\theta = 30°$ discharging into a stagnant, non-stratified ambient (MNN L/D = 10). Entering this figure with $F \simeq 18$ and $\frac{\Delta T_c}{\Delta T_o} = 0.1$, the location of the plume is found to be at

$$X/D \simeq 25 \text{ and } Z/D \simeq 20$$

For a port diameter of 4.2 ft, the absolute centerline location is at $X \simeq 105$ ft and $Z \simeq 85$ ft measured from the discharge point.

Part 2

With a total depth of 150 ft and a port diameter of 4.2 ft, the dimensionless depth is $Z_0/D \simeq 150/4.2 \simeq 36$. Entering Fig. A-17 with $Z/D \simeq 36$ and $F \simeq 18$, one finds the centerline excess temperature ratio

$$\frac{\Delta T_c}{\Delta T_o} \simeq 0.06.$$

Therefore, the excess temperaure in the center of the plume as it reaches the surface is 0.06 x 20 = 1.2° F.

Entering Fig. A-18 with $Z/D \simeq 36$ and $F \simeq 18$, it is found that

$$W/D = 25$$

Therefore, the width of the plume as it reaches the surface is

$$25 \times 4.2 \simeq 105 \text{ ft}$$

The approximte length of the plume can be found from the total diffuser length plus the growth of the plume on the ends as follows:

$$\text{Length} \simeq (N - 1)(L/D)(D) + W$$
$$\simeq (9)(10)(4.2) + 105 = 480 \text{ ft}$$

Variatons of Problem 4 have been solved and results listed in Table VII, where Case 1 is the problem just discussed. Similar procedure to the latter has been used throughout. As a point of interest when comparing the results of this problem with Problem 2, the 2° F temperature difference at the surface required in that problem is satisfied in all cases here by using a multiple port diffuser.

TABLE VII

Variations on Problem 4 Showing Several Discharge Conditions and Diffuser Jet Spacings
(Plant Size 1000 MW)

Case	1	2	3	4	5	6
No. of Ports	10	10	10	100	100	100
Port Dia. D (ft)	4.2	4.2	4.2	1.34	1.34	1.34
Port Spacing L/D	10	10	10	1.5	1.5	1.5
Froude Number	18	18	18	30	30	30
Discharge Angle θ (degree)	30	0	90	30	0	90
Diffuser Length (ft)	378	378	378	200	200	200
Plume Location at X(ft)	105	127	0	96	134	0
ΔT_C = 2° F Z(ft)	85	30	135	88	47	134
ΔT_C at Surface °F	1.2	1.0	1.8	1.4	1.3	1.6
Plume Width at Surface W(ft)	105	140	64	140	174	100
Plume Length at Surface (ft)	483	518	442	340	374	300
Figure Used	A-17 A-18	A-15 A-16	A-21	A-10 A-11	A-8 A-9	A-14

Example Problem 5

Given:

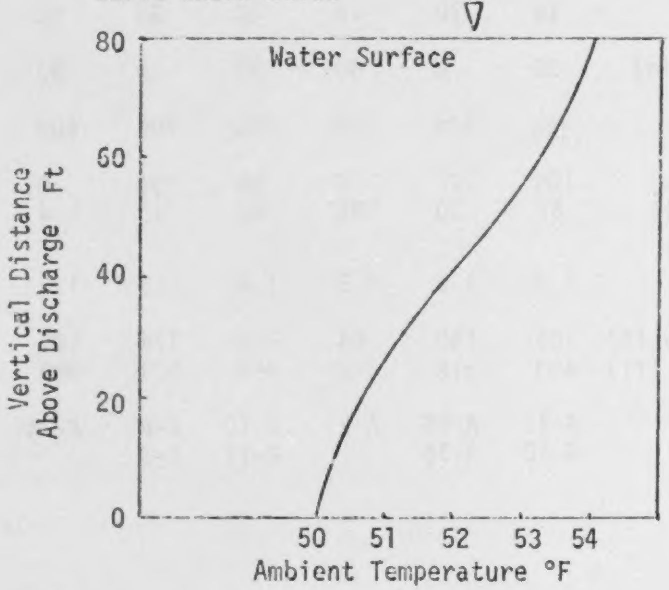
Warm water at 75° F is to be discharged from a multiple port diffuser from the bottom of a stratified lake. The following design conditions apply:

a. The diffuser consists of a single row of nozzles, 1.0 ft in diameter, spaced 1.5 feet apart.

b. Discharge angle $\theta = 0.0°$

c. Discharge Froude number is calculated to be 25

d. The temperature variation within the lake is represented by the curve shown below



Determine:

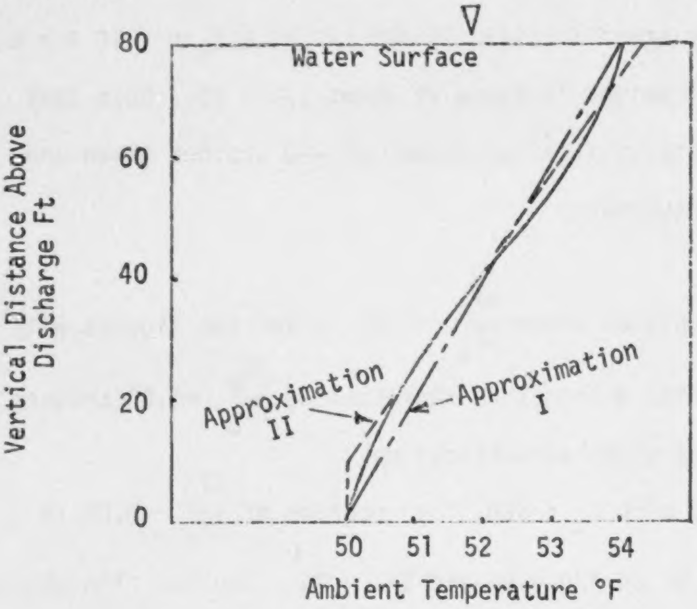
1. The maximum height of rise of the plume.

2. The location of the plume when the difference between the plume centerline and local ambient temperatures is 5 percent of the initial temperature differences, i.e., $\frac{\Delta T_c}{\Delta T_o} = 0.05$.

Solution:

Part 1

The stratification number S_t and the dimensionless distance from discharge to the start of stratification Z_s/D are two parameters in this problem that must be calculated following the procedure outlined in Section III and Fig. 6 in the text. Accordingly, two possible approximations to the given stratification for this problem are shown in the sketch below.



For approximation I, stratification is assumed linear from discharge to the surface, and the above mentioned parameters are:

$$S_t = \frac{\Delta T_o/D}{\Delta T_a/\Delta Z} = \frac{25/1}{4/80} = 500$$

and $Z_s/D = 0$

For approximation II, Stratification is assumed to be linear after an initial 10 ft region that is non-stratified and the alternate parameters of the problem are:

$$S_t = \frac{\Delta T_o/D}{\Delta T_a/\Delta Z} = \frac{25/1}{4.25/70} = 410$$

and $Z_s/D = 10$

Using Fig. B-13 for stratification I, MNS $L/D = 1.5$, $Z_s/D = 0$, $\theta = 0$, and $F = 25$, the terminal height is found to be at $Z/D \approx 75$.

Using Fig. B-17 for stratification II MNS $L/D = 1.5$, $Z_s/D = 10$ $\theta = 0$, and $F = 25$, the terminal height is found at about $Z/D \approx 70$. Note that in this case curves for a stratification number of 410 are not given and thus interpolation was necessary.

Part 2

To determine the location where $\frac{\Delta T_c}{\Delta T_o} = 0.05$, enter the figures with $F = 25$ and locate where the dashed line representing $\frac{\Delta T_c}{\Delta T_o} = 0.05$ crosses the trajectory line for a given stratification.

For approximation I with $S_t = 500$, the location of $\frac{\Delta T_c}{\Delta T_o} = 0.05$ is found from Fig. B-13 to be at $X/D \approx 82$ and $Z/D \approx 26$. The location where the plume centerline temperature reaches the local ambient temperature is found from the (+) mark on the trajectory curve for $F = 25$, $S_t = 500$. This is at $X/D \approx 100$ and $Z/D \approx 43$.

For approximation II using Fig. B-17 with $F = 25$, $S_t = 410$ the location of $\frac{\Delta T_c}{\Delta T_o} = 0.05$ is found to be approximately $X/D \approx 82$ and $Z/D \approx 28$.

Example Problem 6

Given:

The condenser cooling water from a 500 MW fossil-fueled power plant is to be discharged horizontally from a single port diffuser into coastal ocean water at a depth of 100 ft. The following design data apply:

a. Waste heat to cooling water = 1.9×10^9 Btu/hr

b. Condenser ΔT (ΔT_o) = 25° F

c. Discharge angle θ = 0.0°

d. Discharge velocity U_j = 10 ft/sec

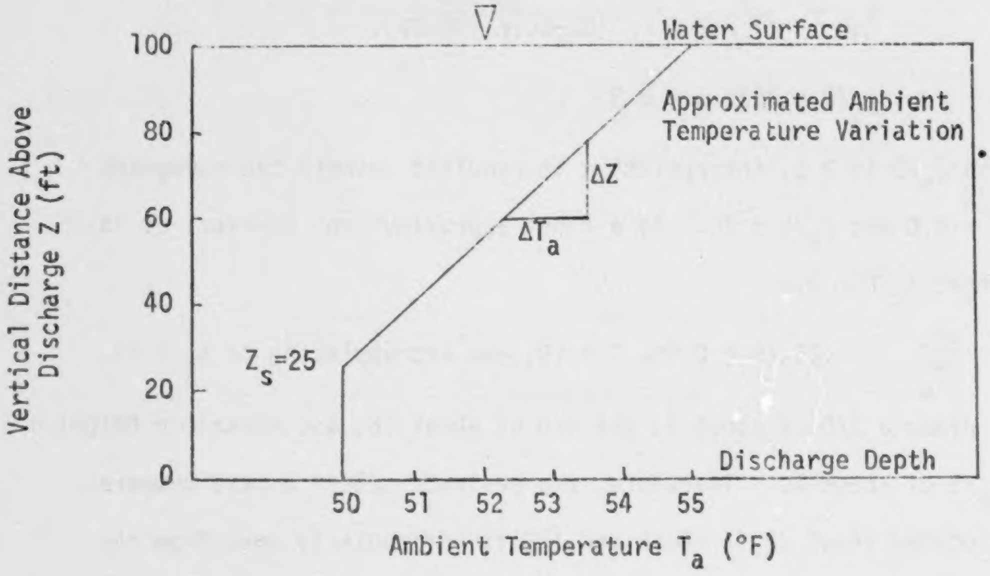
e. Salinity = 40 ppt

f. The ambient water is stagnant and is stratified. The stratification is approximated by the graph given below.

Determine:

1. The maximum height of the plume rise.

2. The location of the plume when its centerline temperature is 1.25° F above the local ambient temperature.



Solution:

Parts 1 and 2

The diffuser port diameter (D) and the discharge Froude number are calculated following the procedure outlined in Problem 1, i.e.,

$$Q = \frac{1.9 \times 10^9 \text{ Btu/hr}}{(64 \text{ lb/ft}^3)(1.0 \text{ Btu/lb-°F})(25\text{°F})(3600 \text{ sec/hr})} = 330 \text{ ft}^3\text{/sec}$$

$$A = \frac{330 \text{ ft}^3\text{/sec}}{10 \text{ ft/sec}} = 33 \text{ ft}^2$$

$$D = (4 \times 33/3.14)^{1/2} = 6.5 \text{ ft}$$

$$F = GU_j(D)^{-1/2} \simeq 3.0 \times 10 \times (6.5)^{-1/2} \simeq 11.7$$

Following the procedure of Section III, the stratification number S_t and dimensionless distance from discharge to the start of stratification number Z_s/D are obtained from the information given on the graph for approximating the ambient stratification. Thus,

$$S_t = \frac{\Delta T_o/D}{\Delta T_a/\Delta Z} = \frac{25/6.5}{(55-50)/(100-25)} = 58$$

and $Z_s/D = 25/6.5 = 3.8$

Since Z_s/D is 3.8, interpolation is required between the nomograms for $Z_s/D = 0.0$ and $Z_s/D = 10$. As a first approximation, however, it is assumed that $Z_s/D = 0.0$.

For $\frac{\Delta T_c}{\Delta T_o} = 1.25/25 = 0.05$, $F = 10$, and extrapolating to $S_t = 58$, Fig. B-1 gives a Z/D of about 5, and X/D of about 18, and a maximum height of rise Z_{max}/D of about 10. Therefore, the desired 1.25° F excess temperature is located about 33 ft above and 120 ft horizontally away from the point of discharge. The maximum height of rise is about 65 ft above discharge.

Variations of Problem 6 have been solved using the nomograms in Appendix B. The results are tabulated in Table VIII where Case 1 was just discussed. Note that multiple as well as single port diffuser problems are treated in Table VIII.

If the reader finds his problem outside the range of parameters covered in nomograms as in the above, he may either choose the next closest parameter or come nearer to the answer by extrapolation. The extrapolation procedure is arbitrary. In the above example Z_{max}/D, for instance, was found by plotting the terminal heights against S_t for $S_t = 2500, 1000, 500$ and 100 all for $F = 10$ as obtained from B-1. The extrapolation to $S_t = 58$ led to the result given for Z_{max}/D.

TABLE VIII

Variations on Problem 6 Showing Several Diffuser Configurations and Discharge Conditions

Case		1	2	3	4	5	6
No. of Ports		1	10	100	100	1	10
Port Dia. D (ft)		6.5	2	.64	.64	6.5	2
Port Spacing L/D		—	10	10	1.5	—	10
Froude Number F		12	21	38	38	12	21
Stratification Number S_t		58	188	580	580	58	188
Z_s/D		0	10	38	38	0	10
Discharge Angle θ (degree)		0	0	0	30	90	90
Plume Location at $\frac{\Delta T_c}{\Delta T_o} = 0.05$	Z(ft)	33	26	14	43	98	50
	X(ft)	120	90	45	35	—	—
Terminal Height (ft)		72	60	45	77	**	**
Figures Used		B-1	B-29	B-33*	B-22	B-4a&b	B-32a&b

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*Fig. A-15 could be used to give more details for $Z/D < 38$ since for Case 3 the fluid is assumed to be non-stratified below Z/D of 38 and the desired dilution to 1.25° F occurs at a Z/D of about 30.

**Plume reaches the water surface

Example Problem 7

450 cfs of warm water is discharged into a river in the general direction of flow at an angle of 30 degrees from the horizontal through 12 equally spaced nozzles. The following conditions apply:

a. The initial temperature difference $\Delta T_o = 30°$ F

b. Discharge velocity $U_j = 10$ ft/sec

c. Average velocity of the ambient water $U_o = 2.5$ ft/sec

d. The river is 40 ft deep and has a uniform temperature of 50° F

Determine:

1. The nozzle spacing so the jet plumes will not merge by the time they reach the river surface.

2. The centerline temperature at the surface.

Solution:

Parts 1 and 2

The port area (A') and diameter (D) of each jet are calculated from the data given as follows:

$Q = 450 \text{ ft}^3/\text{sec}$ $\qquad$ $A' = 45/12 \simeq 3.75 \text{ ft}^2/\text{port}$

$A = \dfrac{450 \text{ ft}^3/\text{sec}}{10 \text{ ft/sec}} = 45 \text{ ft}^2$ $\qquad$ $D \simeq (4 \times 3.75/3.14)^{1/2} = 2.2 \text{ ft}$

From Fig. F-1 with $T_a = 50°$ F, $\Delta T_o = 30°$ F and fresh water, the G factor is found to be about 3.2. Therefore, the Froude number is

$$F = 3.2 \times 10 \times (2.2)^{-1/2} = 21.5 \text{ or } F \simeq 20$$

The jet-to-ambient velocity ratio (k) is:

$$k = U_j/U_o = 10/2.5 = 4.0$$

The nomograms for discharge into non-stratified water with a current are found in Appendix C. For $k = 4$ and $\theta = 30°$, Figures C-13 and C-14 should be used. If the river is 40 ft deep, $Z/D = 40/2.2 \simeq 18$ at the surface. Entering Figures C-13 and C-14 at $Z/D \simeq 18$ and $F \simeq 20$, the values of W/D and $\frac{\Delta T_c}{\Delta T_o}$ at the surface are found to be 11 and 0.02, respectively.

If the plumes are not to merge, then the jet spacing (L) should exceed the plume width at the surface. Thus, L should exceed $2.2 \times 11 \simeq 24$ ft. Since the initial temperature difference was 30° F, the centerline excess temperature of the plumes will be $0.02 \times 30 = .6°$ F when they reach the surface. The location of the plumes when they reach the river surface is found from either Fig. C-13 (or C-14) to be at $X/D \simeq 115$ which is about 250 ft downstream from the discharge point.

Variations of Problem 7 have been solved using the same procedure outlined above. The results are tabulated in Table IX.

TABLE IX

Variations on Problem 7 Showing Several Diffuser Configurations and Discharge Conditions

Case	1	2	3	4	5	6
No. of Ports	12	12	12	5	5	12
Port Diameter D (ft)	2.2	2.2	2.2	3.4	3.4	2.2
River Depth (ft)	40	40	40	40	40	40
Discharge Angle θ (degree)	30	0	90	0	90	90
Froude Number F	21.5	21.5	21.5	17.3	17.3	21.5
k	4	4	4	4	4	8
Port Spacing L (ft)	24	Off chart	23	95	22	18
ΔT_c at Surface (°F)	0.57	<0.3	0.6	0.3	1.5	1.5
Plume Location at Water Surface (ft)	250	>440	308	665	150	49
Figures Used	C-13 C-14	C-7 C-8	C-21 C-22	C-7 C-8	C-21 C-22	C-25 C-26

Example Problem 8

Warm water is discharged vertically from the bottom of a river at a velocity of 10 ft/sec through a 5.0 ft diameter pipe. The discharge Froude number is 20. The river at this location is deep, non-stratified and has an average velocity of 1.0 ft/sec.

Determine:

1. The river depth required so that the centerline excess temperature of the plume will not exceed 2.0 percent of the initial temperature difference.
2. The plume width at this point.

Solution:

Parts 1 and 2

Discharge diameter and Froude number are given:

$$D = 5.0 \text{ ft}$$

$$F = 20$$

The jet-to-ambient velocity ratio is

$$k = U_j/U_o = 10/1 = 10$$

The nomograms for discharge into a moving, non-stratified ambient (RCN) are found in Appendix C. Since RCN plots for $\theta = 90°$ are given for $k = 8$ and 12 but not for $k = 10$, interpolation between the two values of k is required. Entering Figs. C-25 and C-27 with $\frac{\Delta T_c}{\Delta T_o} = 0.02$ and $F = 20$ and interpolating for $k = 10$ gives $Z/D \simeq 31$. Entering Figs. C-26 and C-28 with $Z/D \simeq 31$ and $F = 20$ and interpolating for $k = 10$ gives $W/D \simeq 13$. Therefore, the required depth is $5 \times 31 \simeq 155$ ft at which point the plume width is $5 \times 13 \simeq 65$ ft.

The results of variations to this problem with different values of F, k, and θ are presented in Table X. Note that D is held constant and thus variations in F reflect the effects of different ambient as well as discharge conditions.

TABLE X

Variations on Problem 8 Showing Several Discharge Conditions

Case		1	2	3	4
Froude Number F		20	20	50	50
Port Diameter D (ft)		5	5	5	5
Velocity Ratio k		10	4	8	4
Discharge Angle θ (degree)		90	0	90	0
Plume Location at $\frac{\Delta T_c}{\Delta T_o} = 0.02$	X(ft)	185	650	540	500
	Z(ft)	155	38	150	15
Width at $\frac{\Delta T_c}{\Delta T_o} = 0.02$	W(ft)	65	99	80	113
Figures Used		C-25 C-26 C-27 C-28	C-7 C-8	C-25 C-26	C-7 C-8

Example Problem 9

Given:

A 1000 MW nuclear power plant discharges its cooling water at 20° F above ambient at a velocity of 10 ft/sec through three ports spaced 40 ft apart. River conditions are as follows:

a. Depth = 40 ft

b. Temperature = 50° F

c. Velocity $U_o = 2.5$ ft/sec

d. The discharge is horizontal in the direction of the current (co-flow).

Determine:

1. If the plumes merge before they reach the surface.

2. The downstream plume location where the centerline temperature is, at most, 1° F above the ambient.

Solution:

Part 1

The port diameter (D) is calculated following the procedure outlined for Problem 2 for a 1000 MW power plant with $\Delta T_o = 20°$ F.

$$Q = 1430 \text{ ft}^3/\text{sec}$$

$$A = 143 \text{ ft}$$

For three equal ports, the area per port is

$$A' = 143/3 = 47 \text{ ft}^2$$

$$D = (4 \times 47/3.14)^{1/2} = 7.7 \text{ ft}$$

For fresh water with $\Delta T_o = 20°$ F and $T_a = 50°$ F, the G factor is found from Fig. F-1 to be about 4.5. Therefore, the discharge Froude number is $F = 4.5 \times 10 \times (7.7)^{-1/2} = 16$.

The jet-to-ambient velocity ratio is

$$k = U_j/U_o = 10/2.5 = 4$$

For a river depth of 40 ft and a jet diameter of 7.7 ft, the surface is at $Z/D \simeq 5.2$. For discharge into a moving, non-stratified ambient, use the nomograms in Appendix C (RCN). Entering Fig. C-8 at $Z/D \simeq 5$ and $F \simeq 16$ gives a value of $W/D \simeq 10$. This gives a plume width $W \simeq 10 \times 7.7 \simeq 77$ ft which is greater than the 40 ft jet spacing, indicating that the plumes have already merged at the water surface.

A plume width of $W/D = 40/7.7 = 5.2$ (i.e., where the plume width equals the port spacing) is obtained at $Z/D \simeq 2.0$. This is where the plumes start to merge.

Part 2

Entering Fig. C-7 with $Z/D = 2.0$ and $F = 16$ gives a value of $\frac{\Delta T_c}{\Delta T_o} = 0.15$ or $\Delta T_c = 3°$ F. This indicates that the centerline excess temperature of 1.0° F occurs after the plumes have started to merge. Since information on merging jets in a current are not presently available, only an approximation can be made as to where the lower temperature will be reached.

The exit ports would have to be 77 ft apart to prevent the plumes from merging by the time they reached the surface. If this were the case, a 1° F excess temperature where $\frac{\Delta T_c}{\Delta T_o} = 0.05$ is found from Fig. C-7 to occur just as the plumes reach the surface at $Z/D \simeq 5$ and $X/D \simeq 75$.

Example Problem 10

Given:

Warm water is discharged vertically upward into a deep layer of a large body of moving water. The following conditions are given:

a. Discharge Froude number = 20

b. Discharge port diameter D = 5 ft

c. Discharge velocity = 5 ft/sec

d. Ambient velocity U_o = 1.0 ft/sec

e. Receiving water is linearly stratified with a temperature gradient $\Delta T_a/\Delta Z$ = 0.07° F/ft

f. The initial temperature difference ΔT_o = 20° F

Determine:

1. The location of the plume when the centerline excess temperature is 2° F.

2. If the total depth is 150 ft, does the plume reach the surface?

Solution:

Part 1

The jet-to-ambient velocity ratio is

$$k = U_j/U_o = 5/1 = 5$$

The stratification number S_t is

$$S_t = \frac{\Delta T_o/D}{\Delta T_a/\Delta Z} = \frac{20/5}{0.07} = 57$$

Since the ambient water temperature is linearly stratified throughout, the dimensionless discharge depth Z_s/D is zero.

This problem is for a single jet discharging into a moving, stratified ambient water (RCS). The corresponding nomograms are found in Appendix D. The closest values plotted are for k = 4, S_t = 100, and F = 30, which are found on Figs. D-5 and D-6.

Entering Fig. D-5 with $\frac{\Delta T_c}{\Delta T_o} = 2/20 = 0.1$ and $\theta = 90°$, the location of the plume is found to be at $Z/D \simeq 7$ and $X/D \simeq 5$. This is 35 ft above and 25 ft downstream of the discharge point.

Part 2

It is seen from Fig. D-5 that the maximum height of rise for vertical discharge with the given ambient conditions is approximately at Z/D = 19 or $Z \simeq 95$ ft. Since the total depth is 150 ft, the plume will not reach the surface. This is particularly true since the stratification number is 60 rather than 100 as used in the calculations.

Variations of this problem with different discharge and ambient conditions have been solved and the results are listed in Table XI.

TABLE XI

Variations on Problem 1C Showing Several Discharge Configurations and Ambient Conditions

Case	1	2	3	4	5	6
Froude Number F	20	20	20	10	75	75
Port Dia. D (ft)	5	5	5	10	2	2
Temperature Gradient (°F/ft)	.07	.07	.07	.025	.025	.025
S_t	60	60	60	80	400	400
Discharge Angle θ (degree)	90	0	90	90	90	0
k	4	4	2	2	4	4
Plume Location X (ft)	25	200	33	80	16	76
at $\Delta T_c = 2°$ F Z (ft)	35	5	25	50	16	0
Terminal Height (ft)	95	*	*	125	*	*
Figures Used	D-5	D-5	D-3	D-1	D-15	D-15

* Off Chart

Example Problem 11

Given:

Condenser cooling water is discharged vertically upward into shallow sea water. The following conditions apply:

a. Discharge velocity U_j = 15 ft/sec

b. Discharge diameter D = 5 ft

c. Ambient is stagnant and non-stratified with a salinity of 40 ppt and a temperature of 60° F

d. The discharge depth is 50 ft

e. The initial temperature difference ΔT_o = 30° F

Determine:

The temperature at the center of the plume when it reaches the surface.

Solution:

From Fig. F-1 with T_a = 60° F, ΔT_o = 30° F and salinity of 40 ppt, the value of G is found to be about 2.5. Therefore, the Froude number is

$$F = GU_j(D)^{-1/2} = 2.5 \times 15 \times (5)^{-1/2} = 16.7$$

The shallow water nomograms of Appendix E are used for this problem. The appropriate figure to enter is E-2 for Z/D = 50/5 = 10. From this figure and for a Froude number of 17, it is found that $\frac{\Delta T_c}{\Delta T_o} = 0.4$ at the surface. Therefore, the temperature at the center of the plume as it reaches the surface is $60 + 0.4 \times 30 \simeq 72$° F.

Variations of this problem with different discharge conditions and depths have been solved and the results are listed in Table XII.

TABLE XII

Variations of Problem 11 Showing Surface Temperatures for Several Discharge Conditions

Case	1	2	3	4
Port Dia. D (ft)	5	5	2	10
Discharge Velocity U_j (ft/sec)	15	15	10	10
Froude Number F	16.7	16.7	17.8	7.9
Depth (ft)	50	200	10	100
Surface Temperature ΔT_c (°F)	12	1.5	24	10
Figures Used	E-2	E-1	E-3	E-2

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APPENDIX A

Nomograms for Discharge into Stagnant, Non-Stratified Water, (RNN, MNN)

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TABLE I

Figure Numbers Corresponding to Plume Behavior
From Submerged Diffusers Discharging into
Stagnant, Non-stratified Water

Diffuser		Discharge Angle			
		0°	30°	60°	90°
RNN Single Jet		A-1,2	A-3,4	A-5,6	A-7
MNN Multiple Jet Diffuser	L/D = 1.5	A-8,9	A-10,11	A-12,13	A-14
	L/D = 10	A-15,16	A-17,18	A-19,20	A-21
	L/D = 20	A-22,23	A-24,25	A-26,27	A-28
	L/D = 30	A-29,30	A-31,32	A-33,34	A-35

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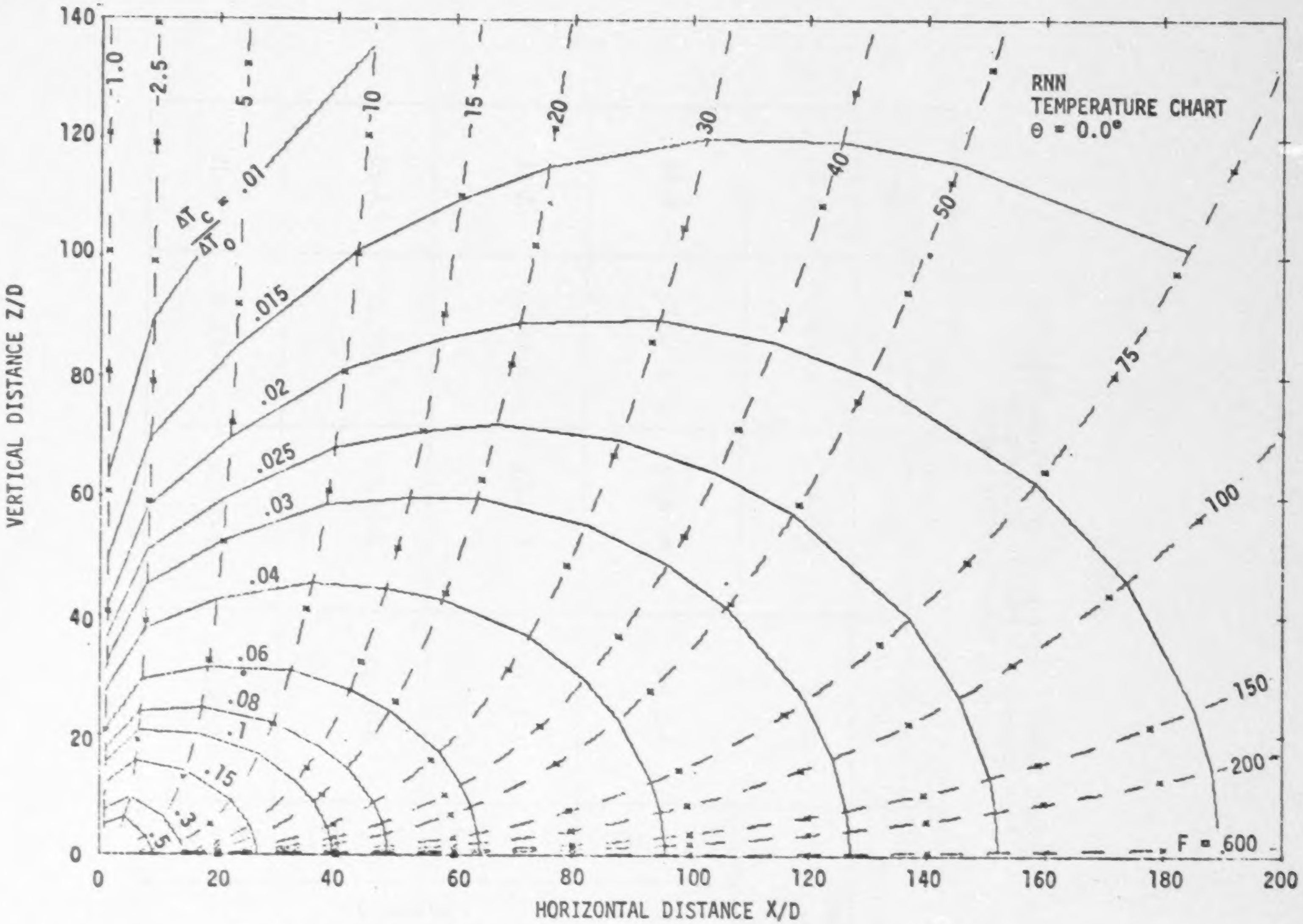

Fig. A-1 Temperature-Trajectory Chart for a Single Jet Discharging into a Non-Stratified, Stagnant Large Body of Water: RNN, θ = 0°

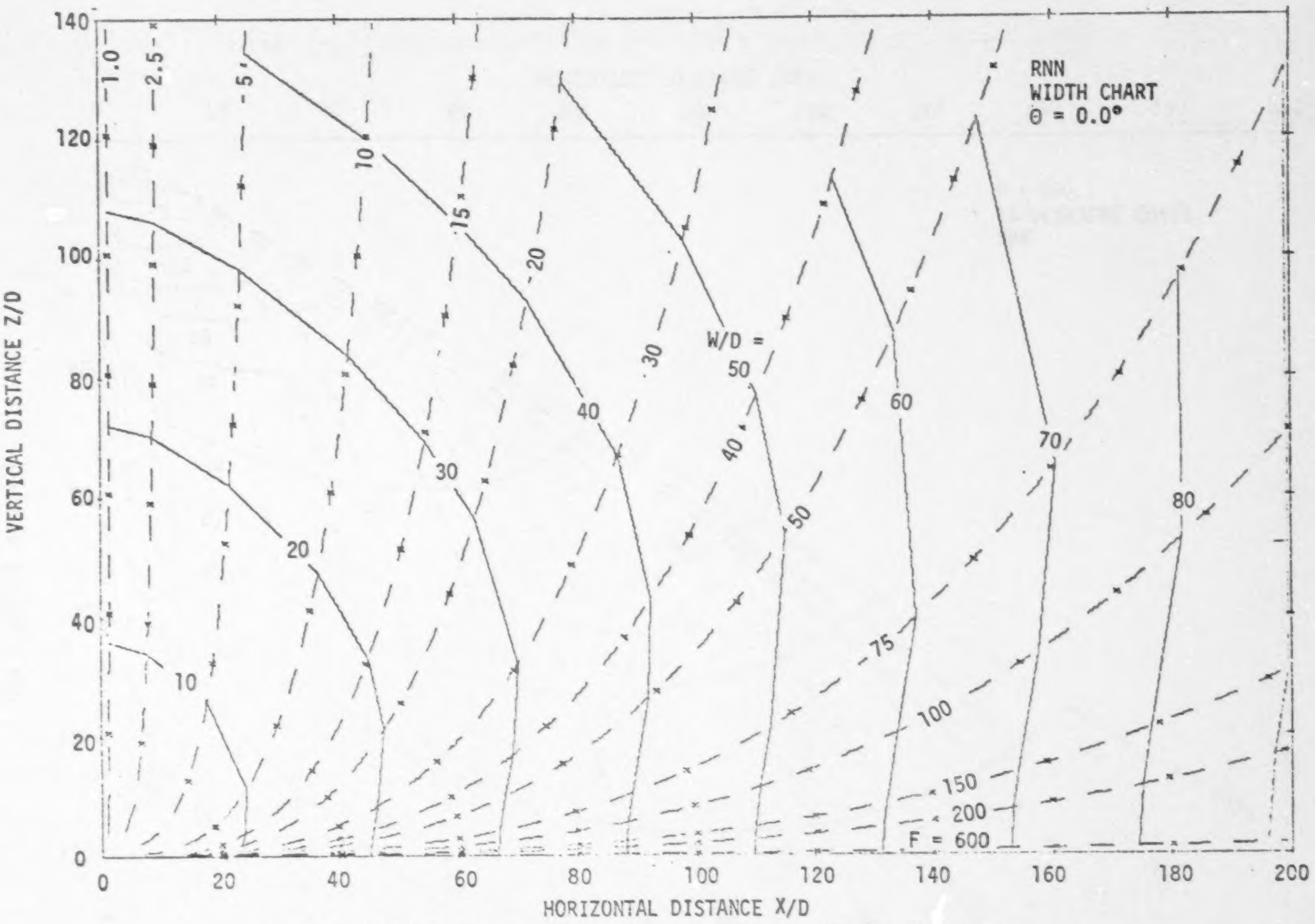

Fig. A-2 Width-Trajectory Chart for a Single Jet Discharging into a Non-Stratified, Stagnant Large Body of Water: RNN, θ = 0°

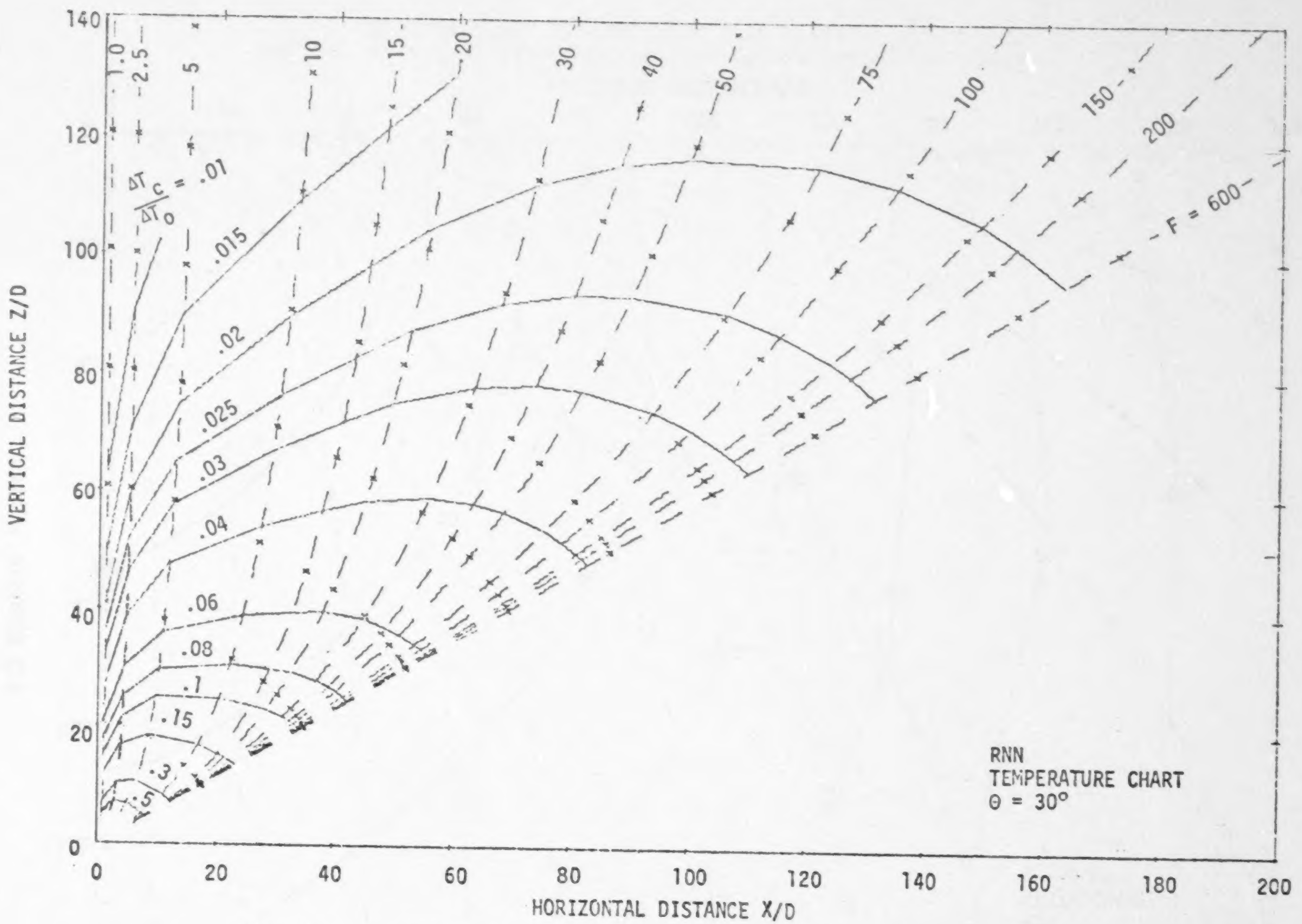

Fig. A-3 Temperature-Trajectory Chart for a Single Jet Discharging into a Non-Stratified, Stagnant Large Body of Water: RNN, θ = 30°

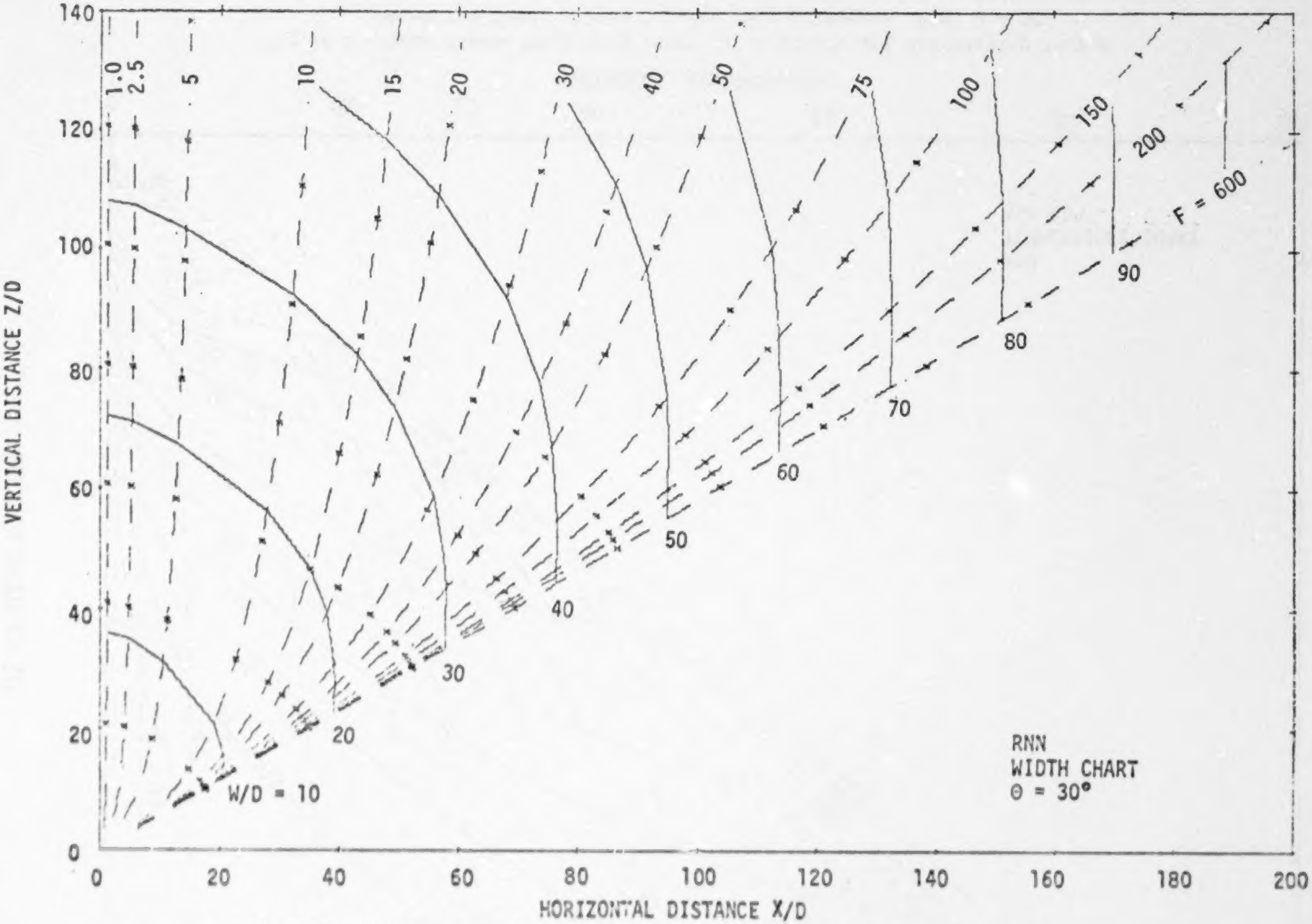

Fig. A-4 Width-Trajectory Chart for a Single Jet Discharging into a Non-Stratified, Stagnant Large Body of Water: RNN, θ = 30°

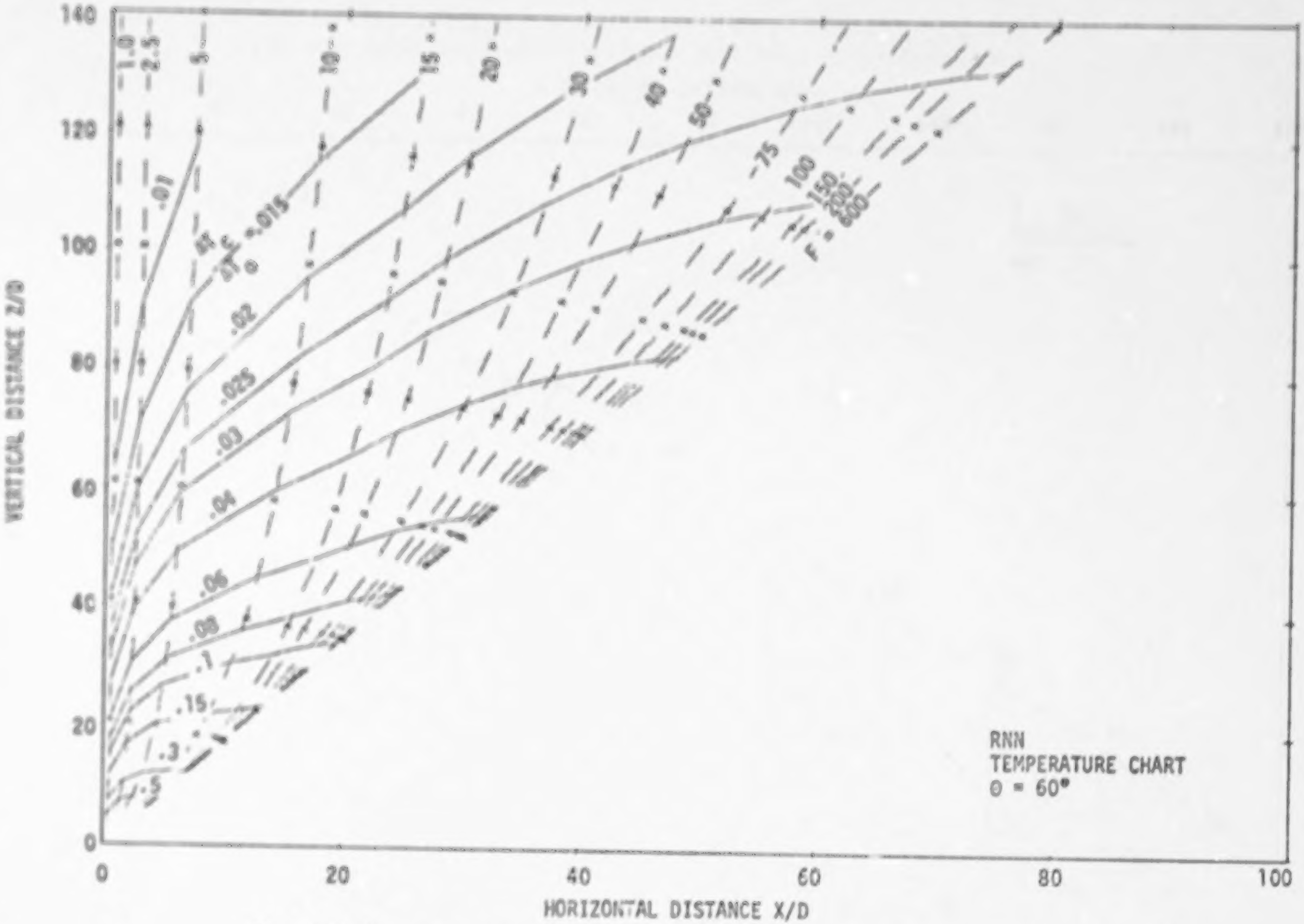

Fig. A-5 Temperature-Trajectory Chart for a Single Jet Discharging into a Non-Stratified, Stagnant Large Body of Water: RNN, θ = 50°

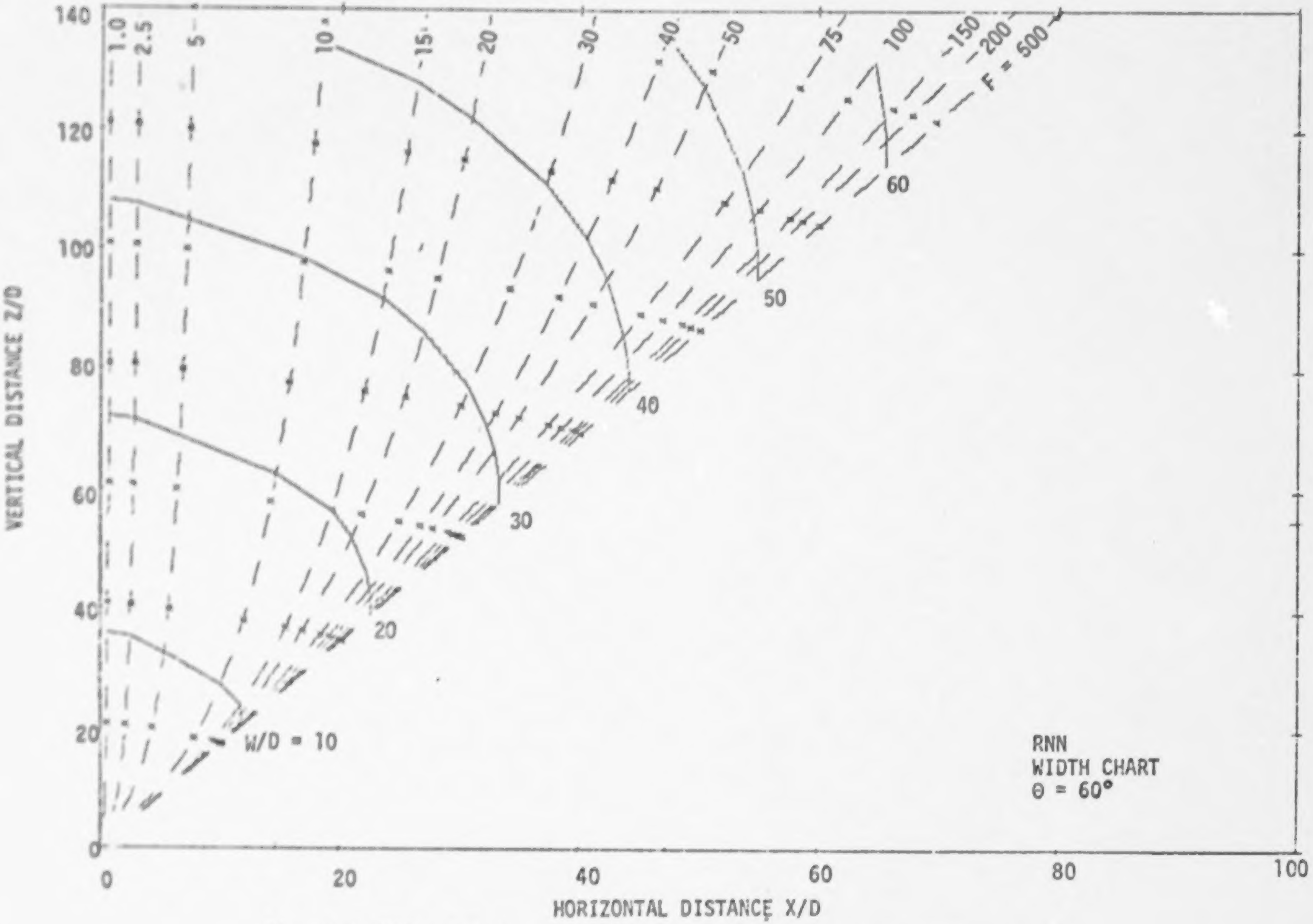

Fig. A-6 Width-Trajectory Chart for a Single Jet Discharging into a Non-Stratified, Stagnant Large Body of Water: RNN, Θ = 60°

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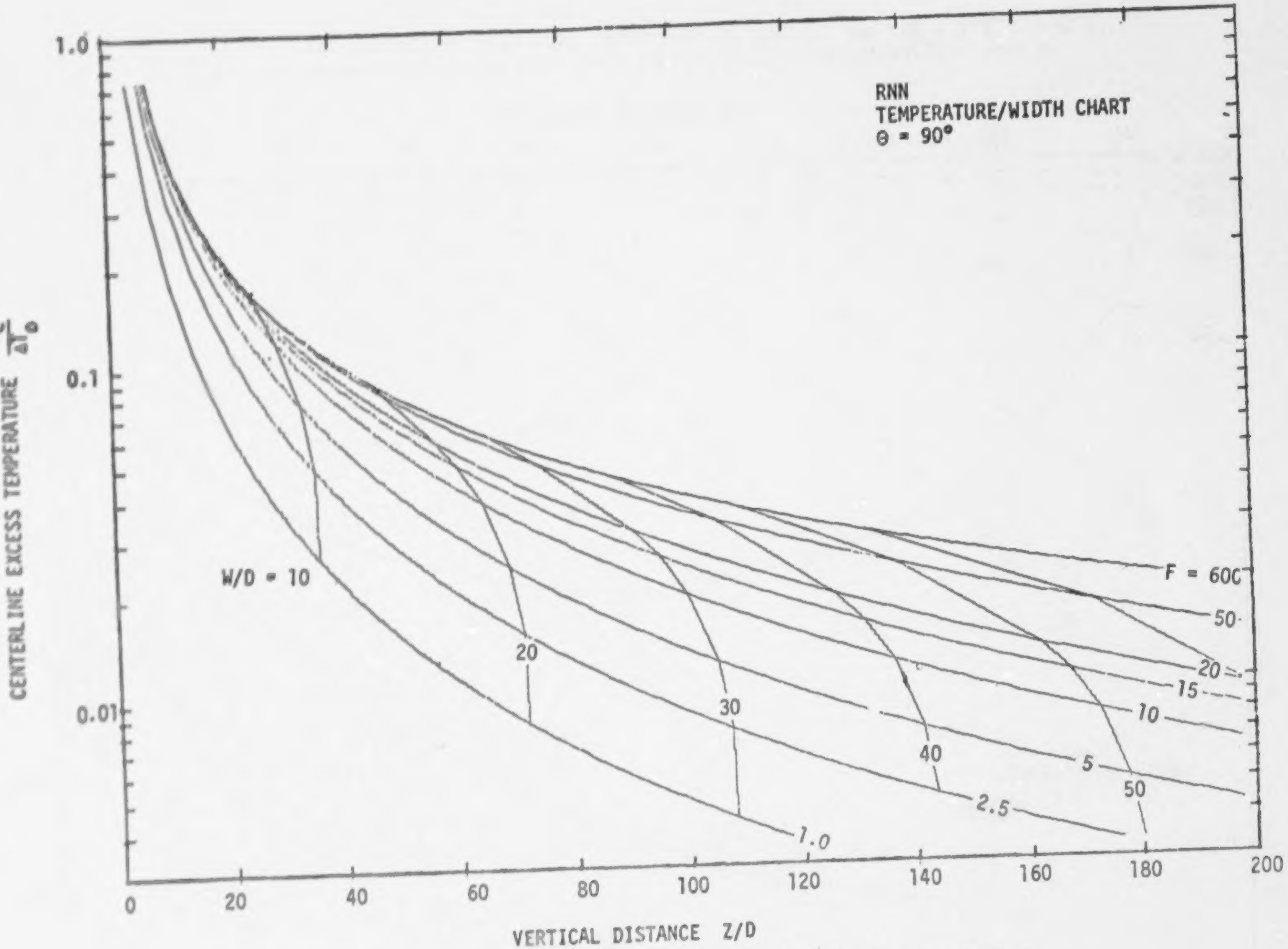

Fig. A-7 Temperature-Width Chart for Single Jets Discharging into a Non-Stratified, Stagnant Large Body of Water: RNN, Θ = 90°

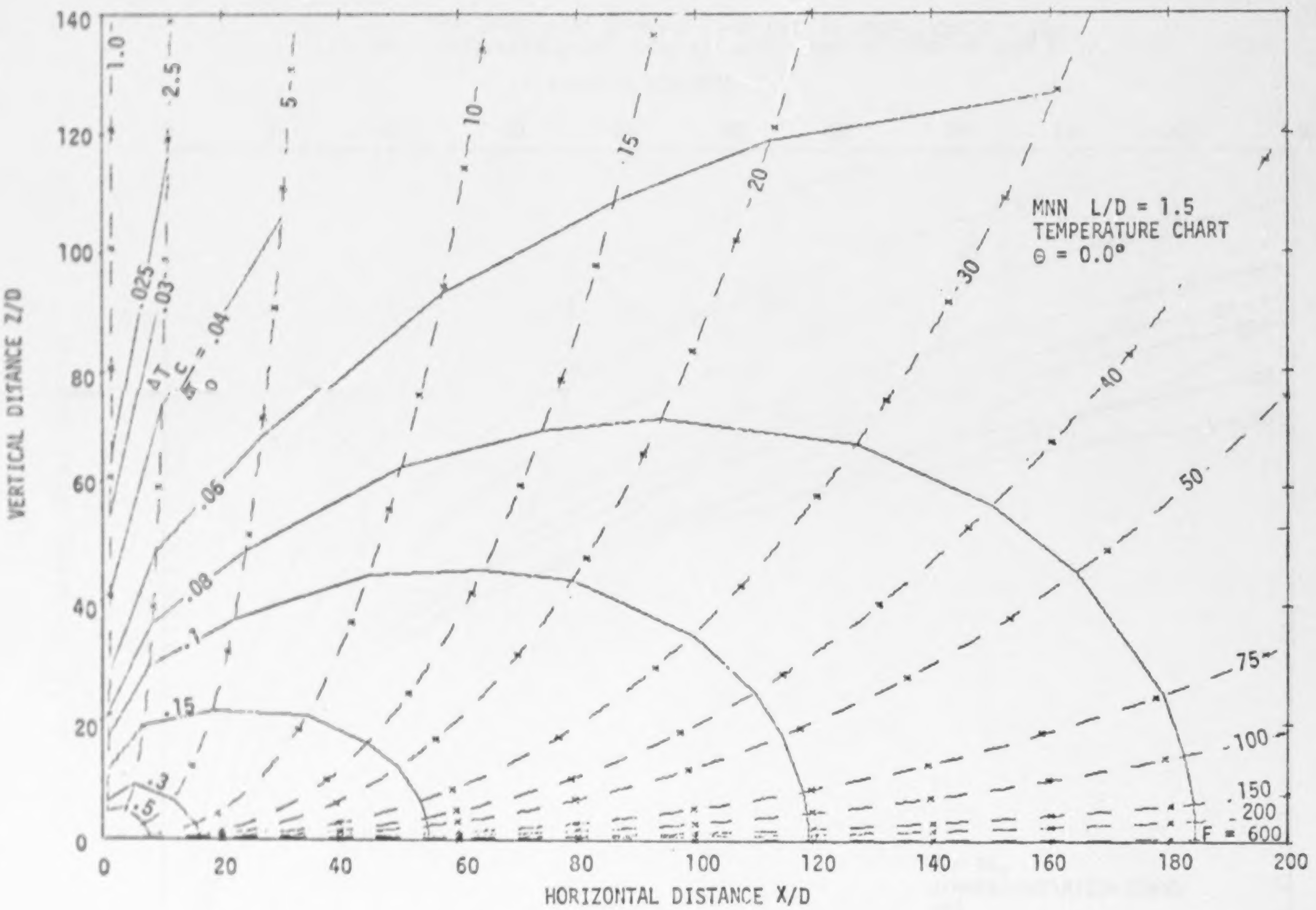

Fig. A-8 Temperature-Trajectory Chart for Multiple Jets Discharging into a Non-Stratified, Stagnant Large Body of Water: MNN L/D = 1.5, Θ = 0.0°

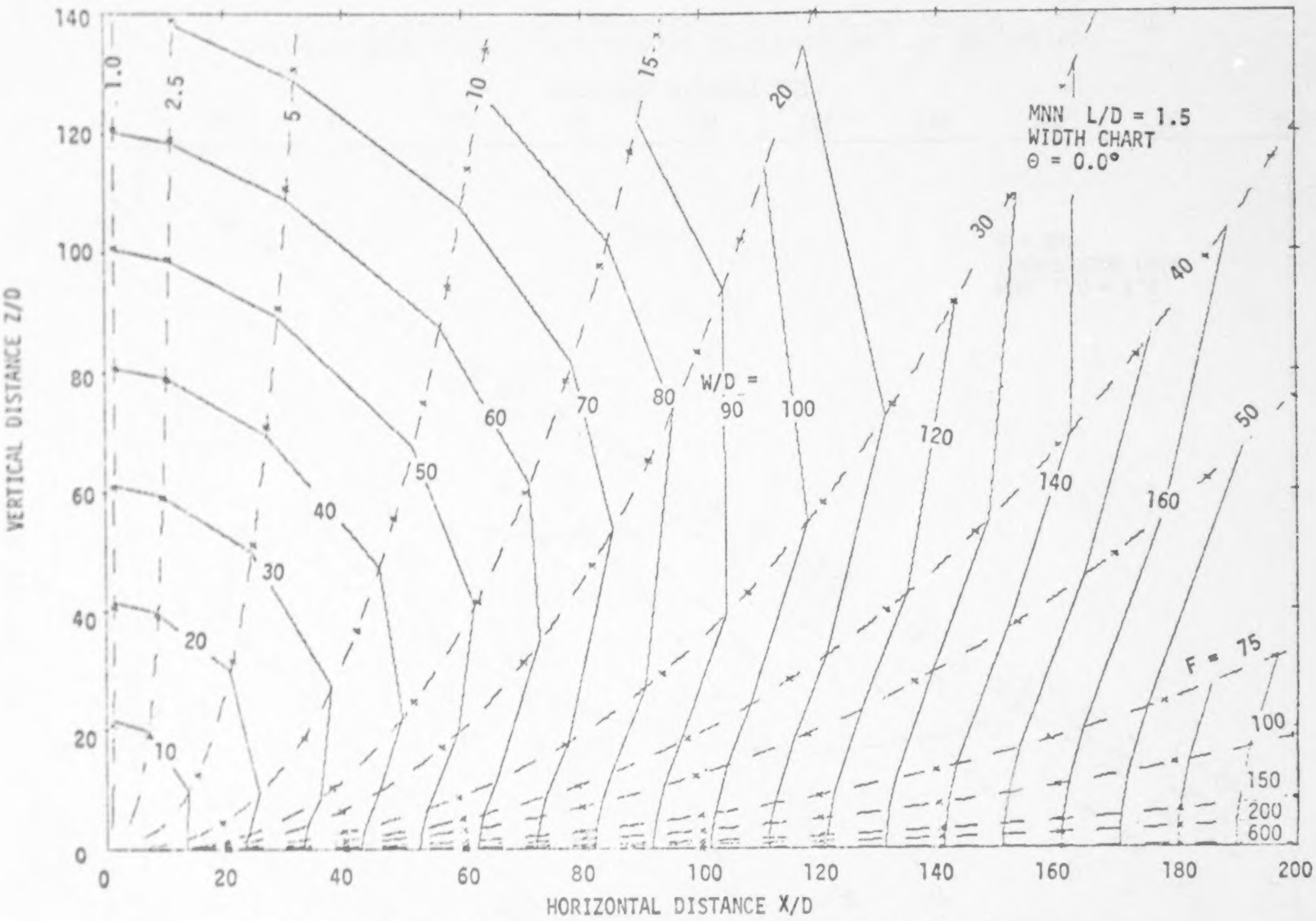

Fig. A-9 Width-Trajectory Chart for Multiple Jets Discharging into a Non-Stratified, Stagnant Large Body of Water: MNN L/D =1.5, θ = 0°

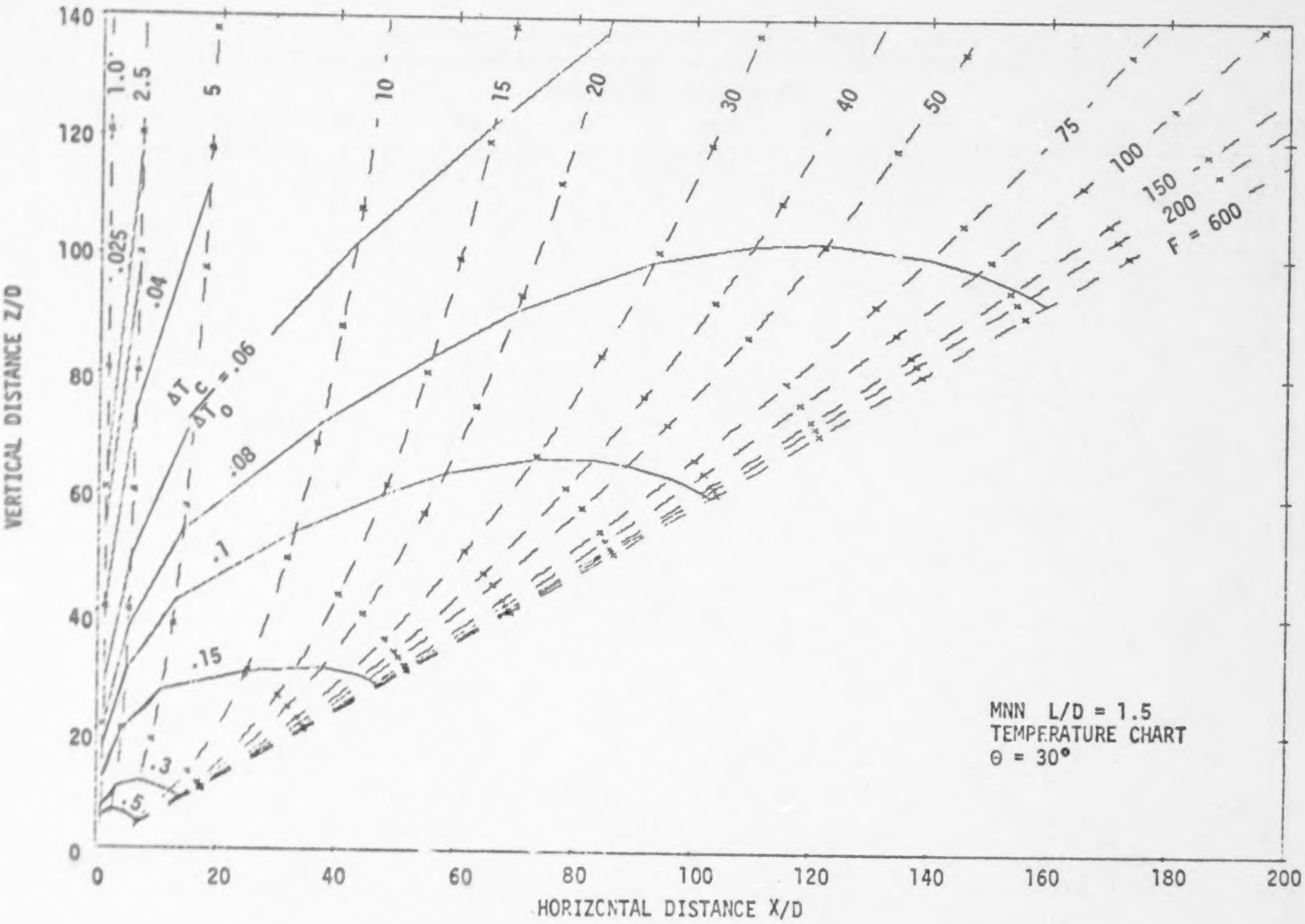

Fig. A-10 Temperature-Trajectory Chart for Multiple Jets Discharging into a Non-Stratified, Stagnant Large Body of Water: MNN L/D = 1.5, Θ = 30°

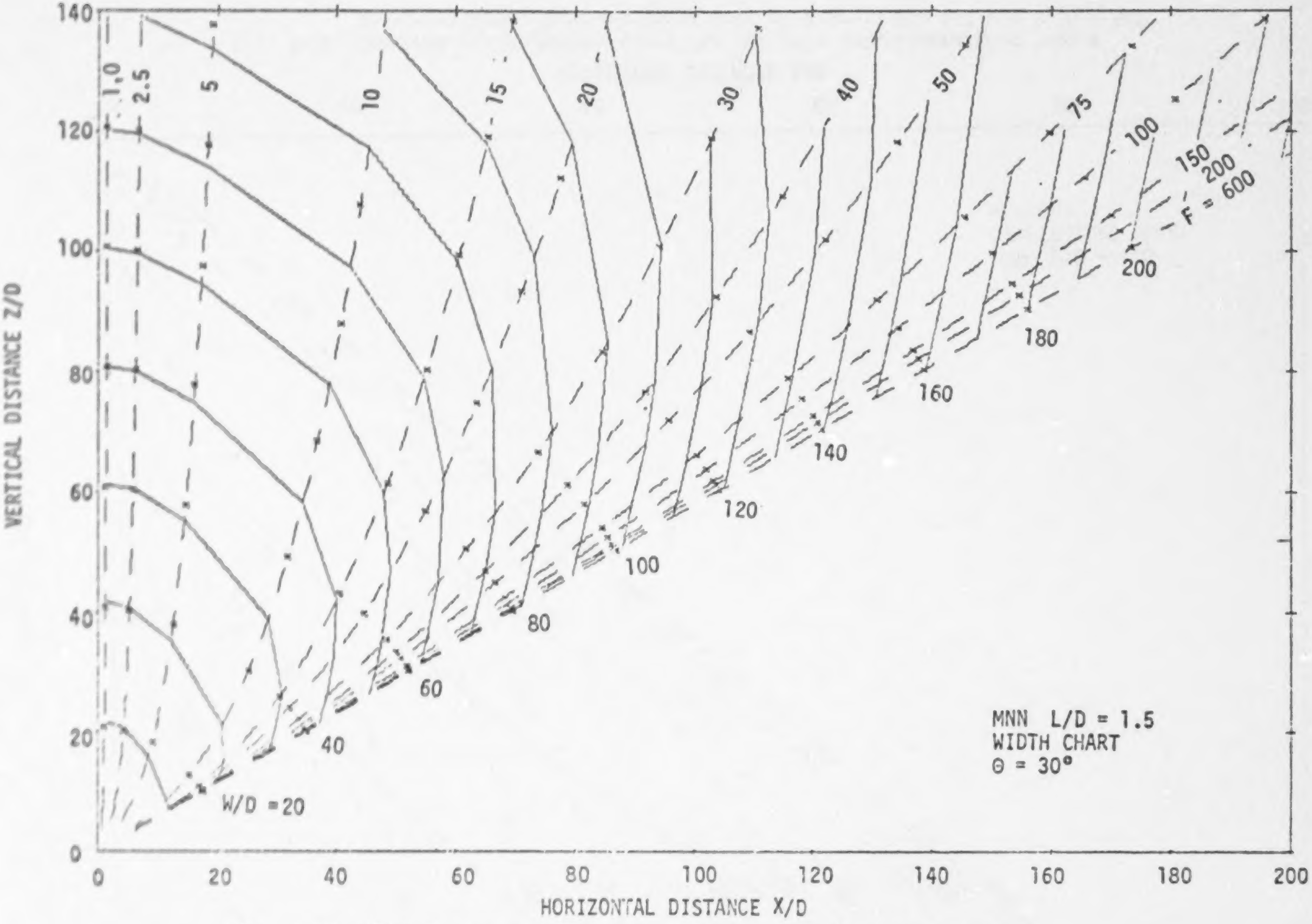

Fig. A-11 Width-Trajectory Chart for Multiple Jets Discharging into a Non-Stratified, Stagnant Large Body of Water: MNN L/D = 1.5, Θ = 30°

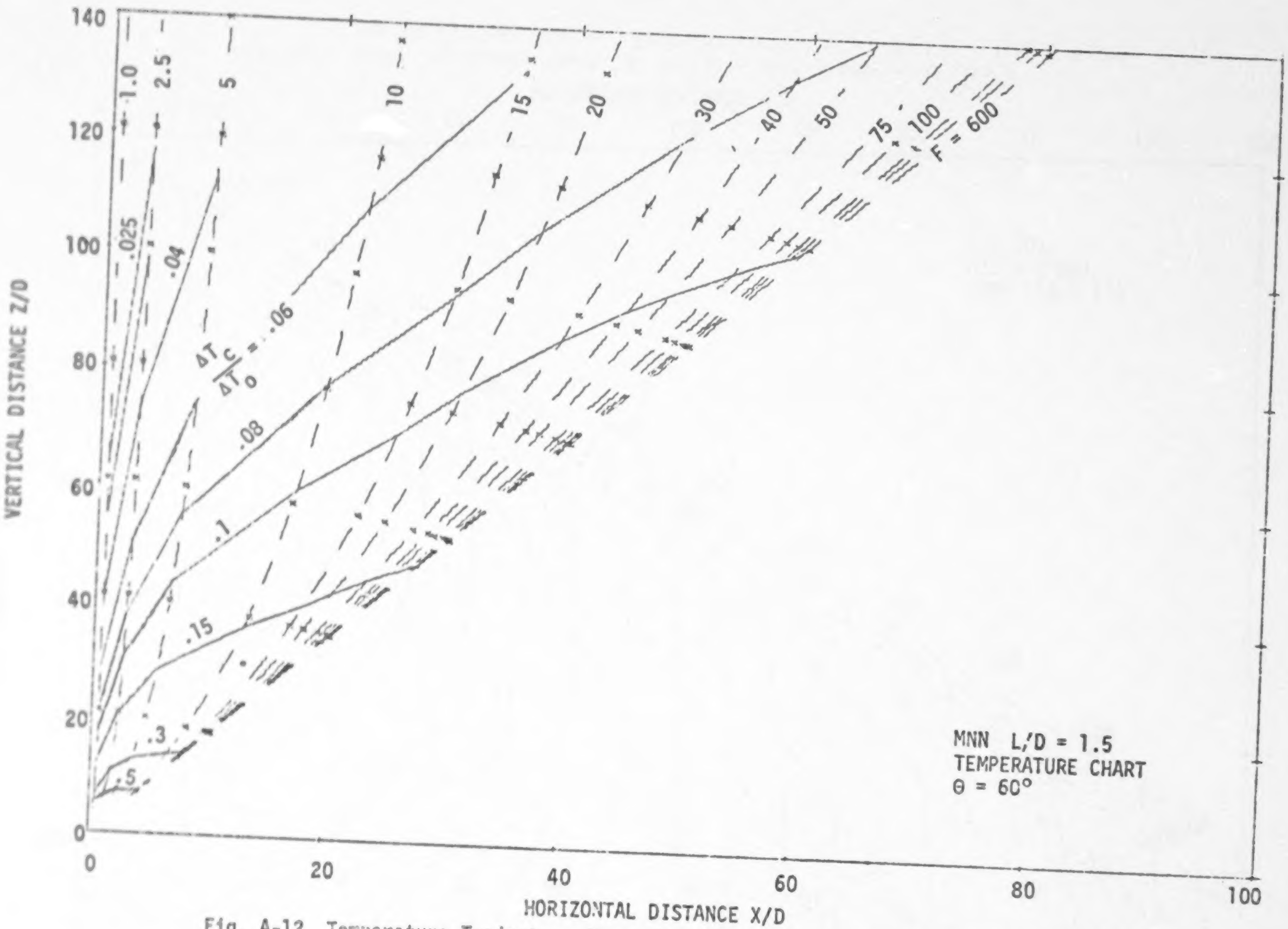

Fig. A-12 Temperature-Trajectory Chart for Multiple Jets Discharging into a Non-Stratified, Stagnant Large Body of Water: MNN L/D = 1.5, θ = 60°

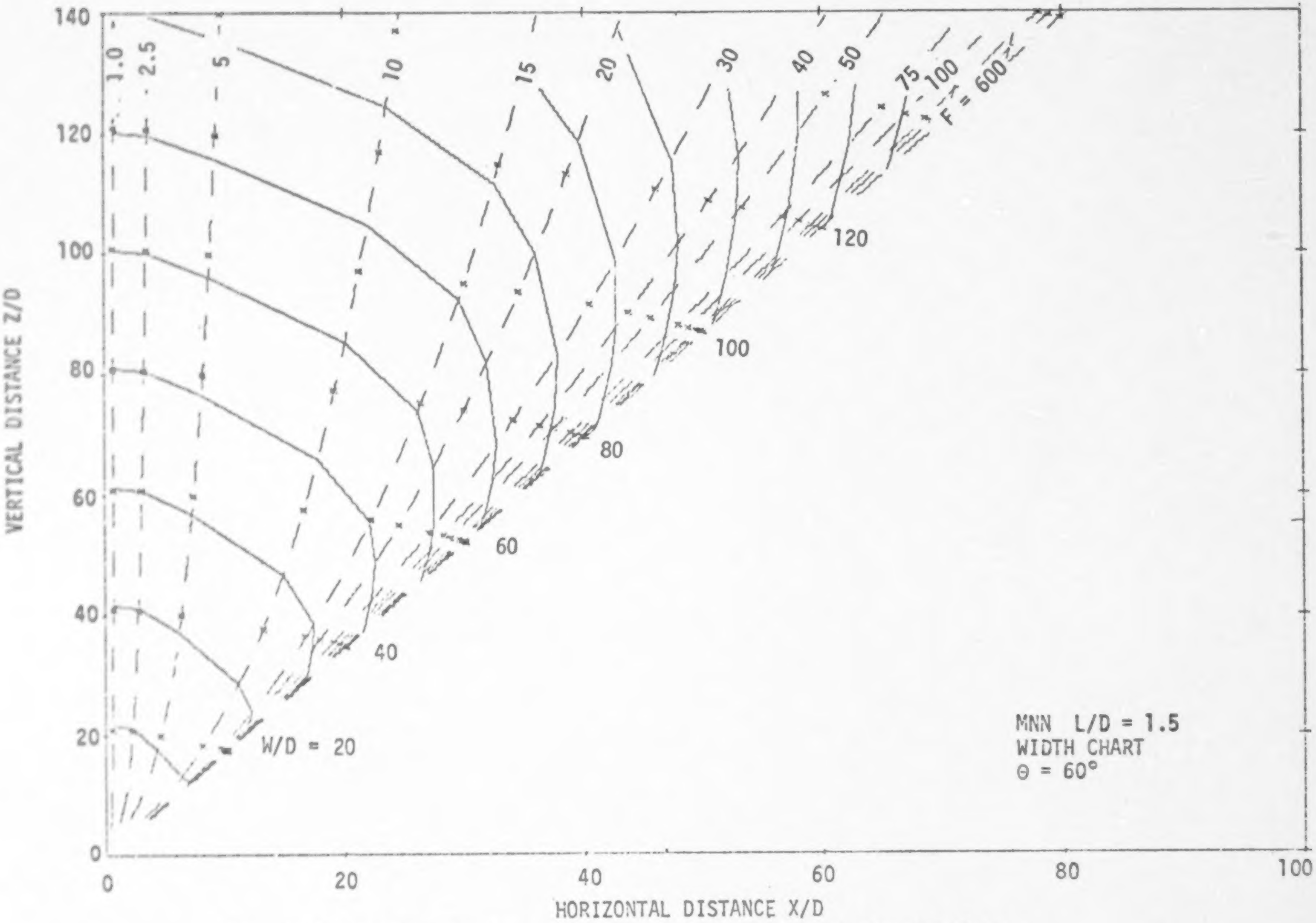

Fig. A-13 Width-Trajectory Chart for Multiple Jets Discharging into a Non-Stratified, Stagnant Large Body of Water: MNN L/D = 1.5, Θ = 60°

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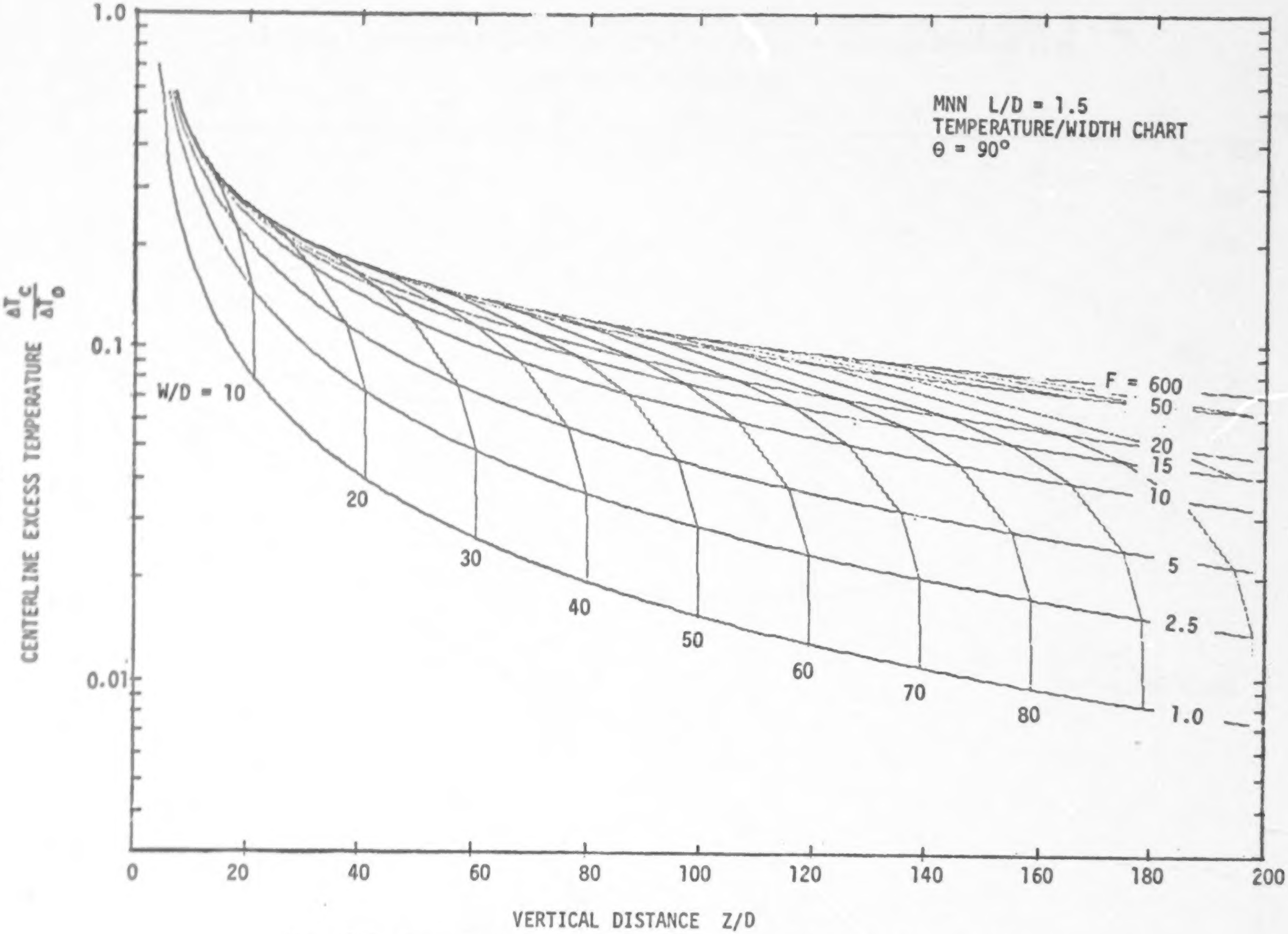

Fig. A-14 Temperature-Width Chart for Multiple Jets Discharging into a Non-Stratified, Stagnant Large Body of Water: MNN L/D = 1.5, Θ = 90°

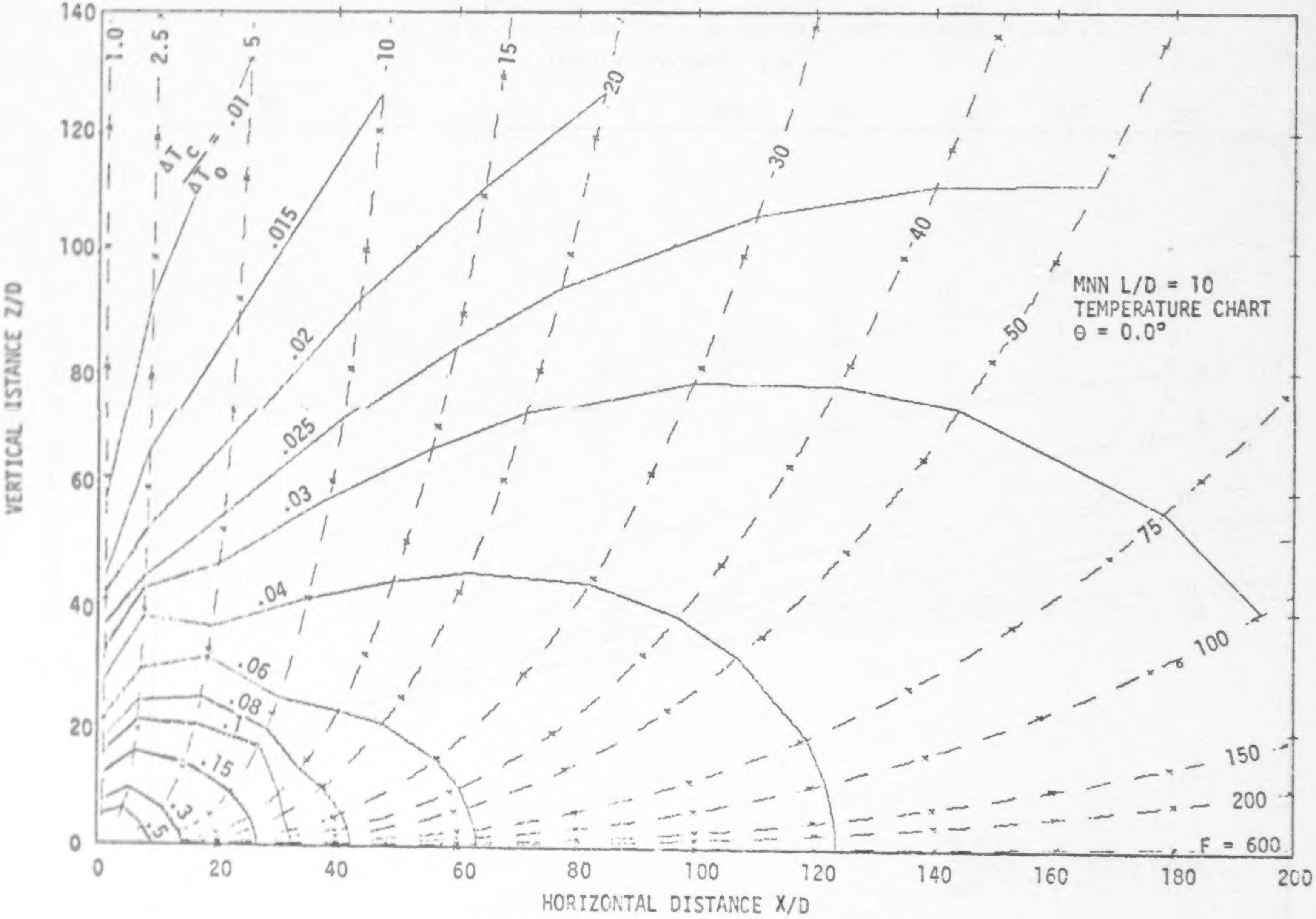

Fig. A-15 Temperature-Trajectory Chart for Multiple Jets Discharging into a Non-Stratified, Stagnant Large Body of Water: MNN L/D = 10, Θ = 0°

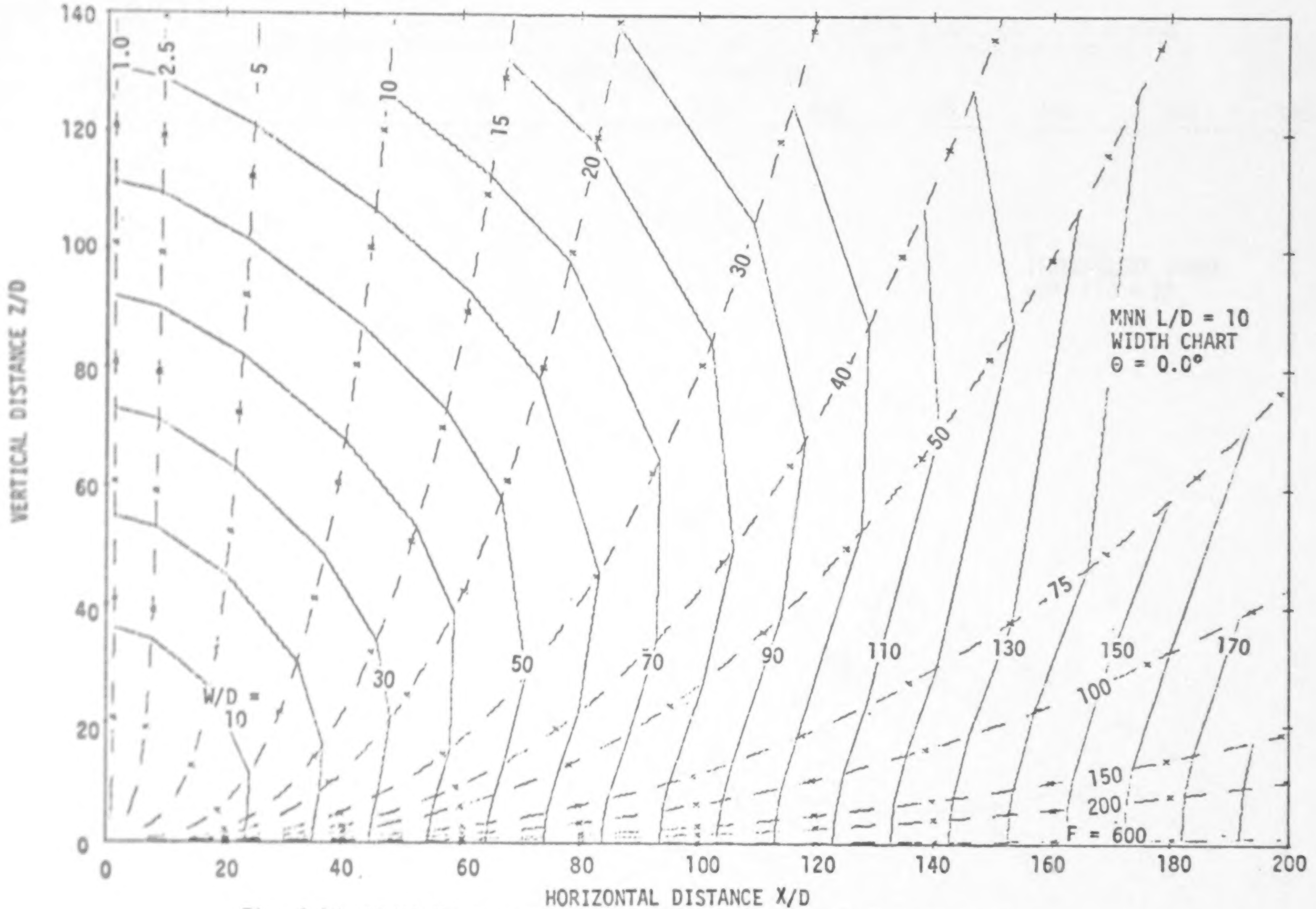

Fig. A-16 Width Trajectory Chart for Multiple Jets Discharging into a Non-Stratified, Stagnant Large Body of Water: MNN L/D = 10, Θ = 0°

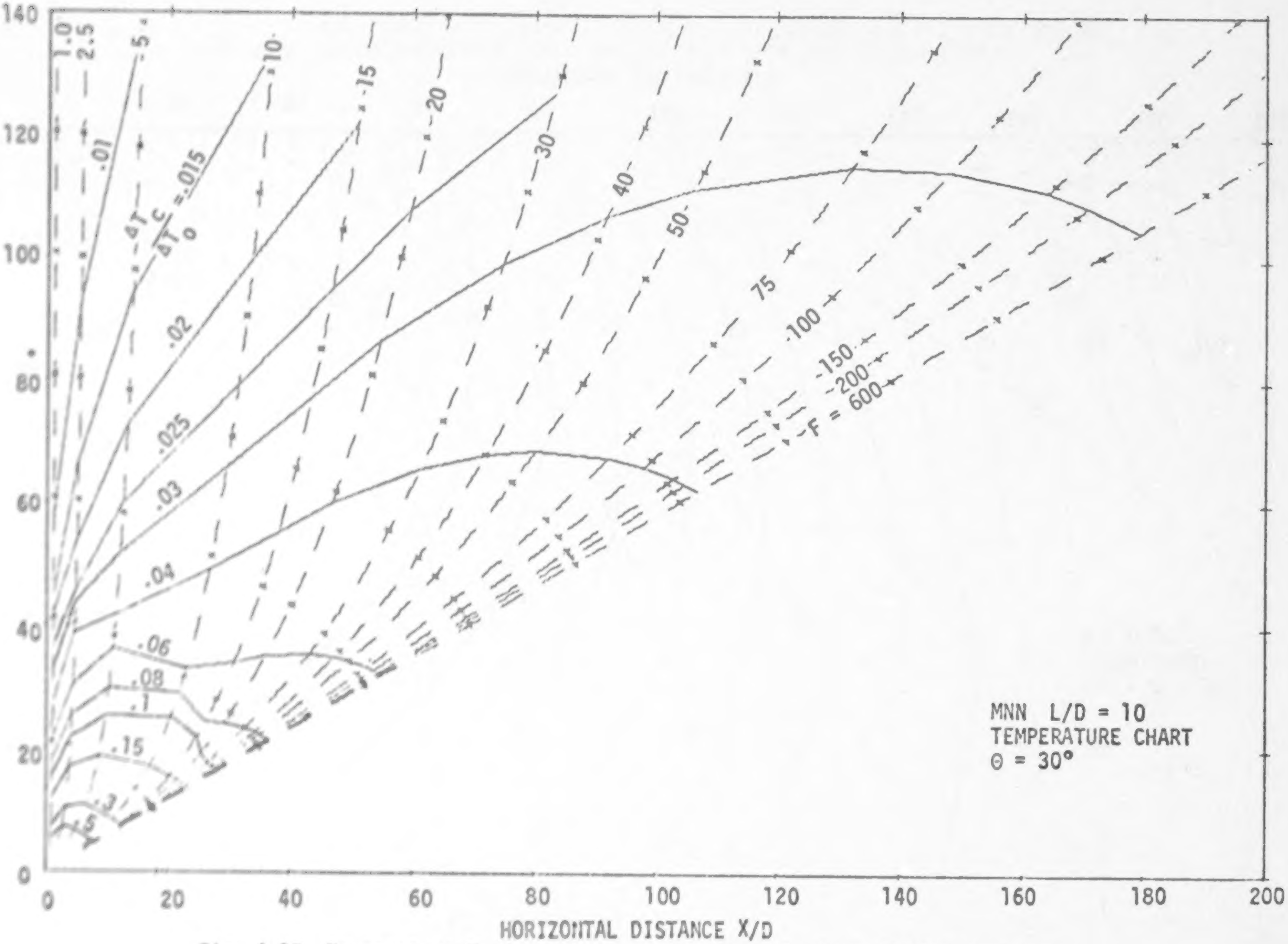

Fig. A-17 Temperature-Trajectory Chart for Multiple Jets Discharging into a Non-Stratified, Stagnant Large Body of Water: MNN L/D = 10, Θ = 30°

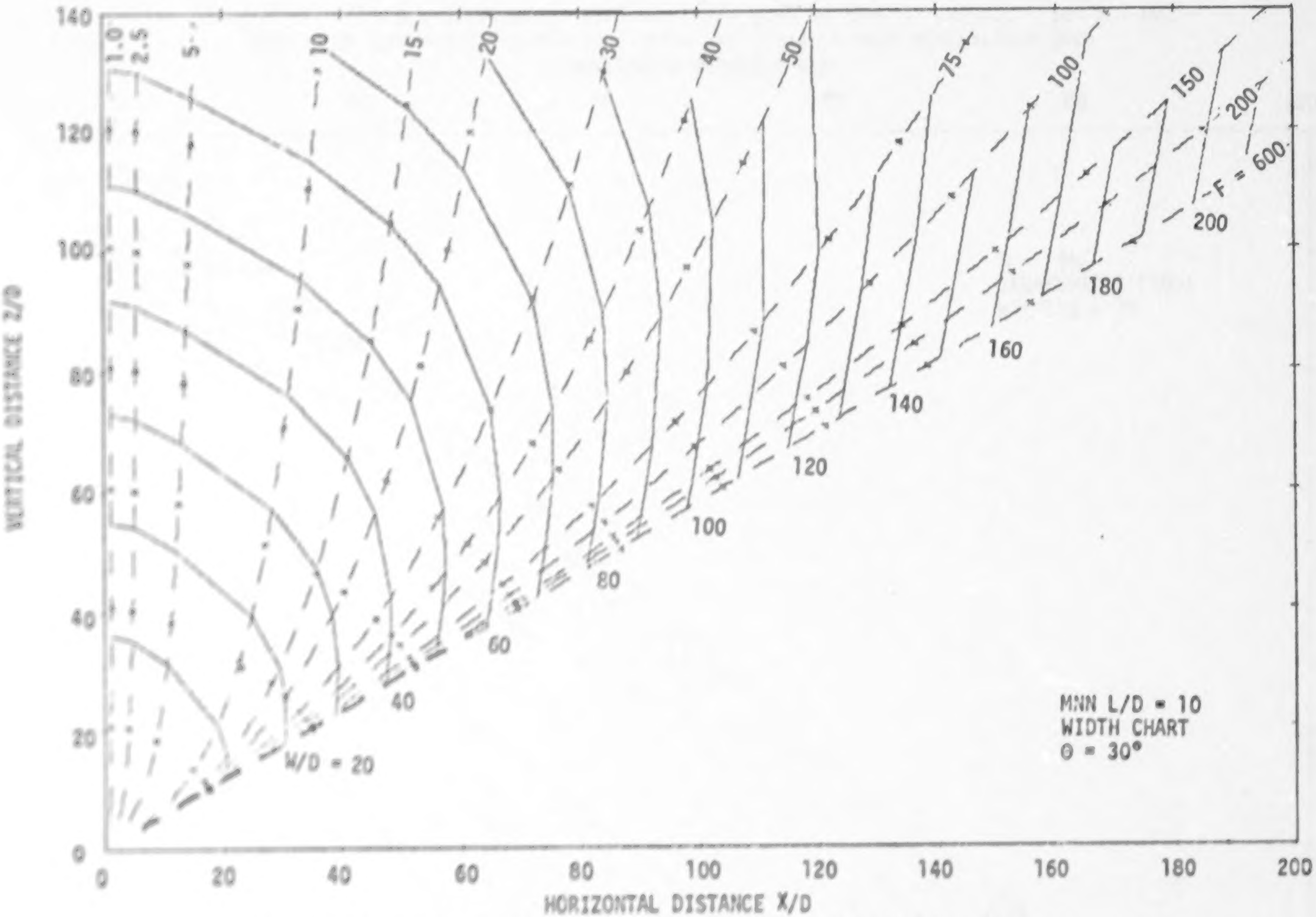

Fig. A-18 Width-Trajectory Chart for Multiple Jets Discharging into a Non-Stratified, Stagnant Large Body of Water: MNN L/D = 10, θ = 30°

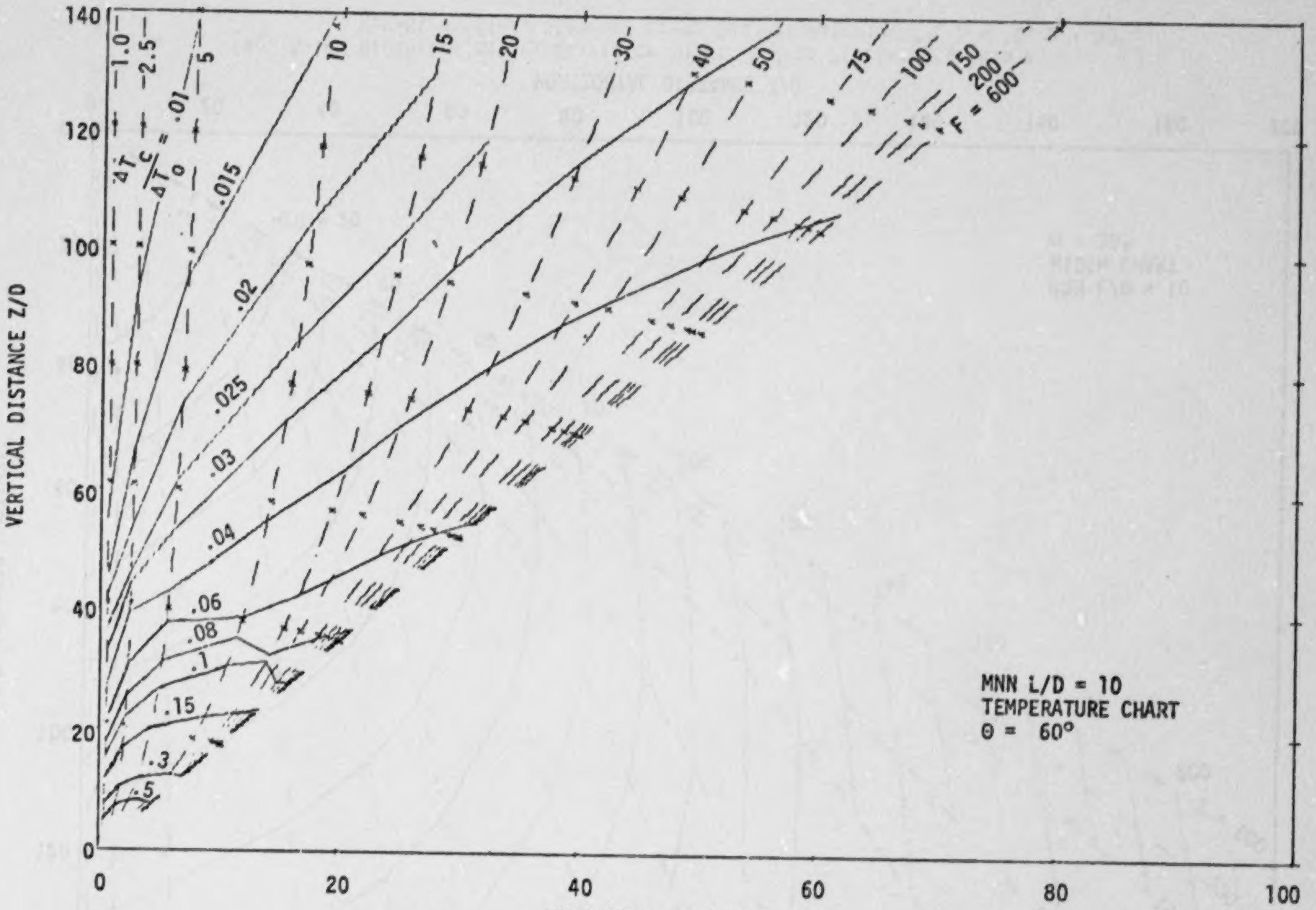

Fig. A-19 Temperature-Trajectory Chart for Multiple Jets Discharging into a Non-Stratified, Stagnant Large Body of Water: MNN L/D = 10, Θ = 60°

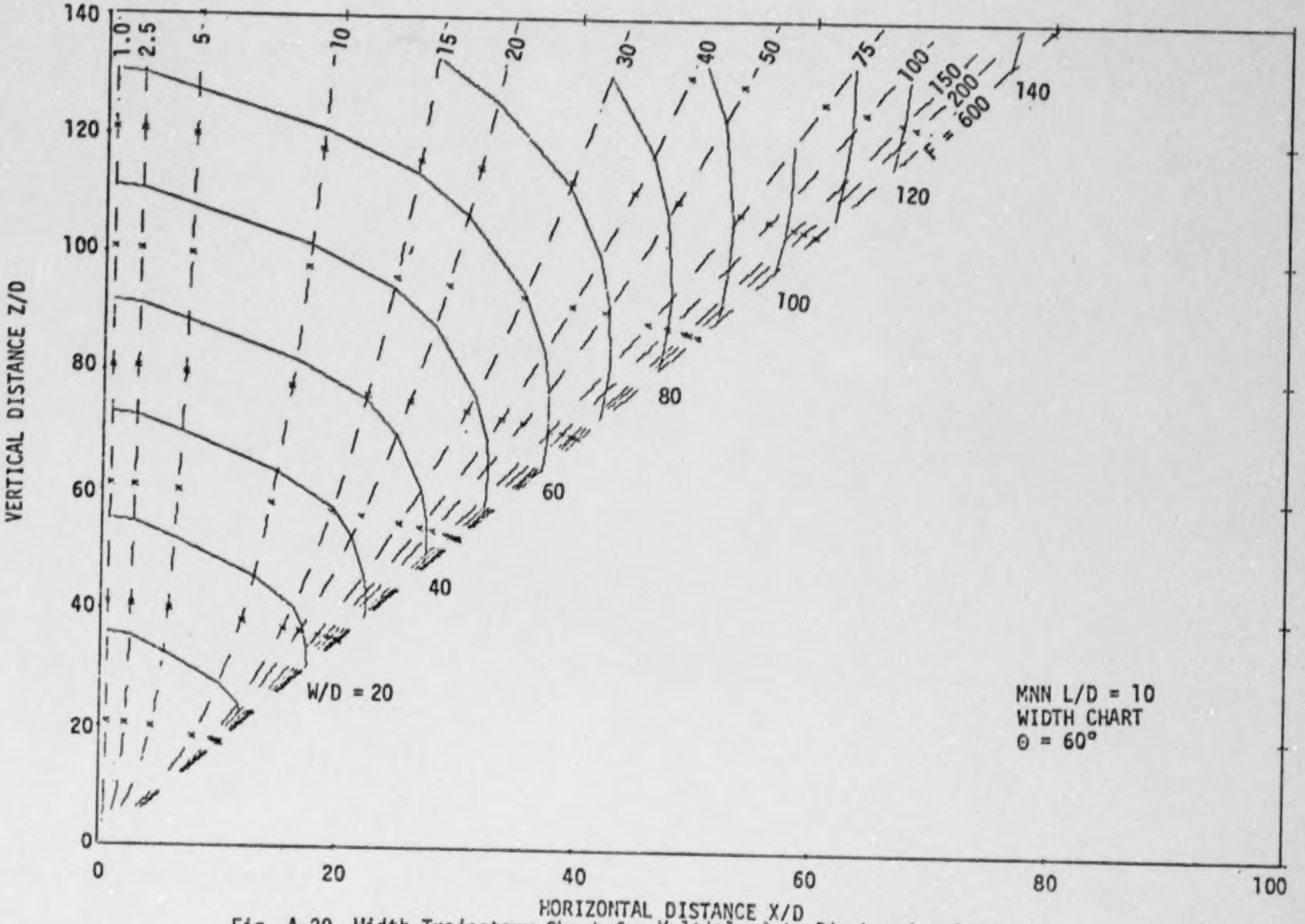

Fig. A-20 Width-Trajectory Chart for Multiple Jets Discharging into a Non-Stratified, Stagnant Large Body of Water: MNN L/D = 10, Θ = 60°

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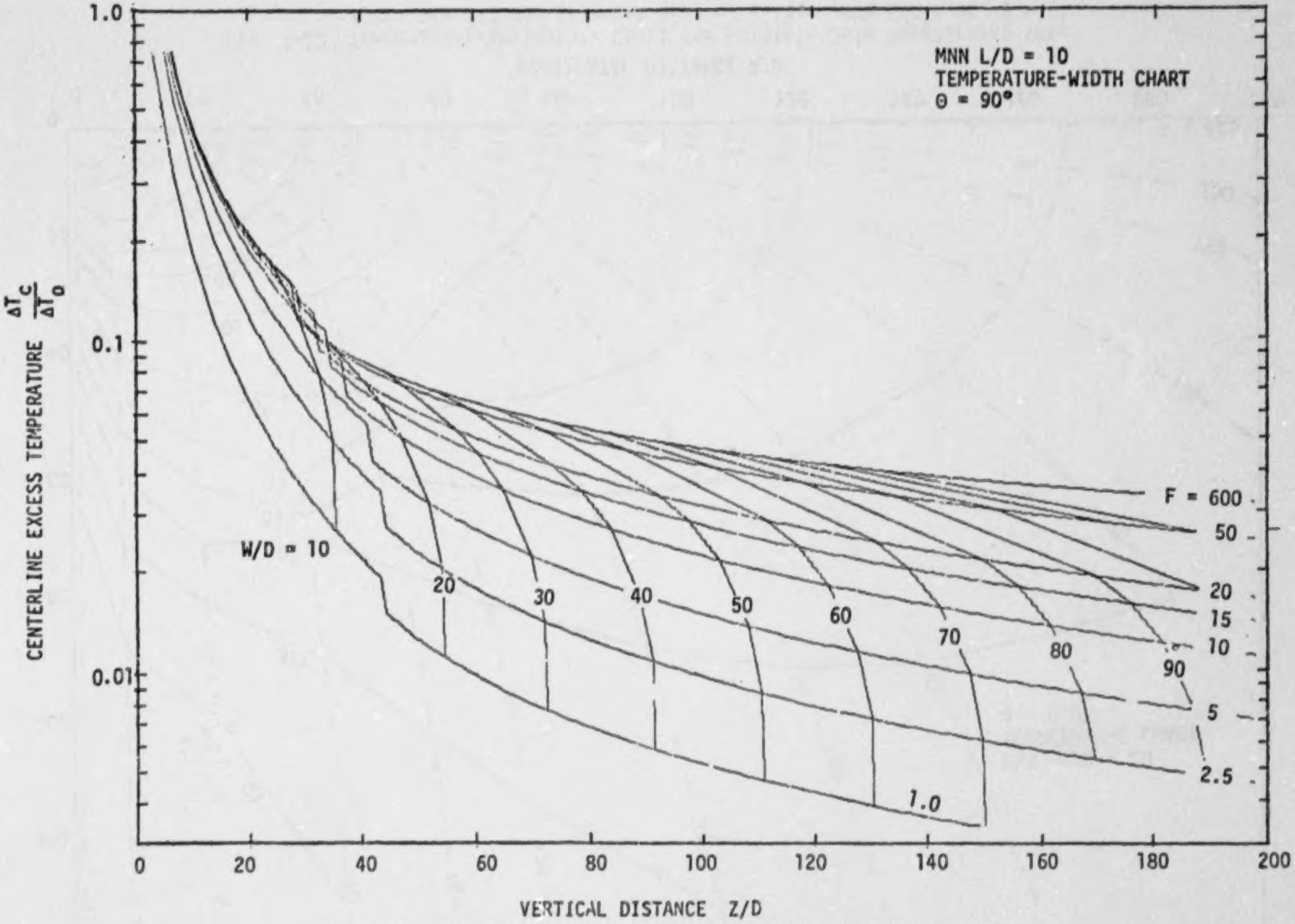

Fig. A-21 Temperature-Width Chart for Multiple Jets Discharging into a Non-Stratified, Stagnant Large Body of Water: MNN L/D = 10, Θ = 90°

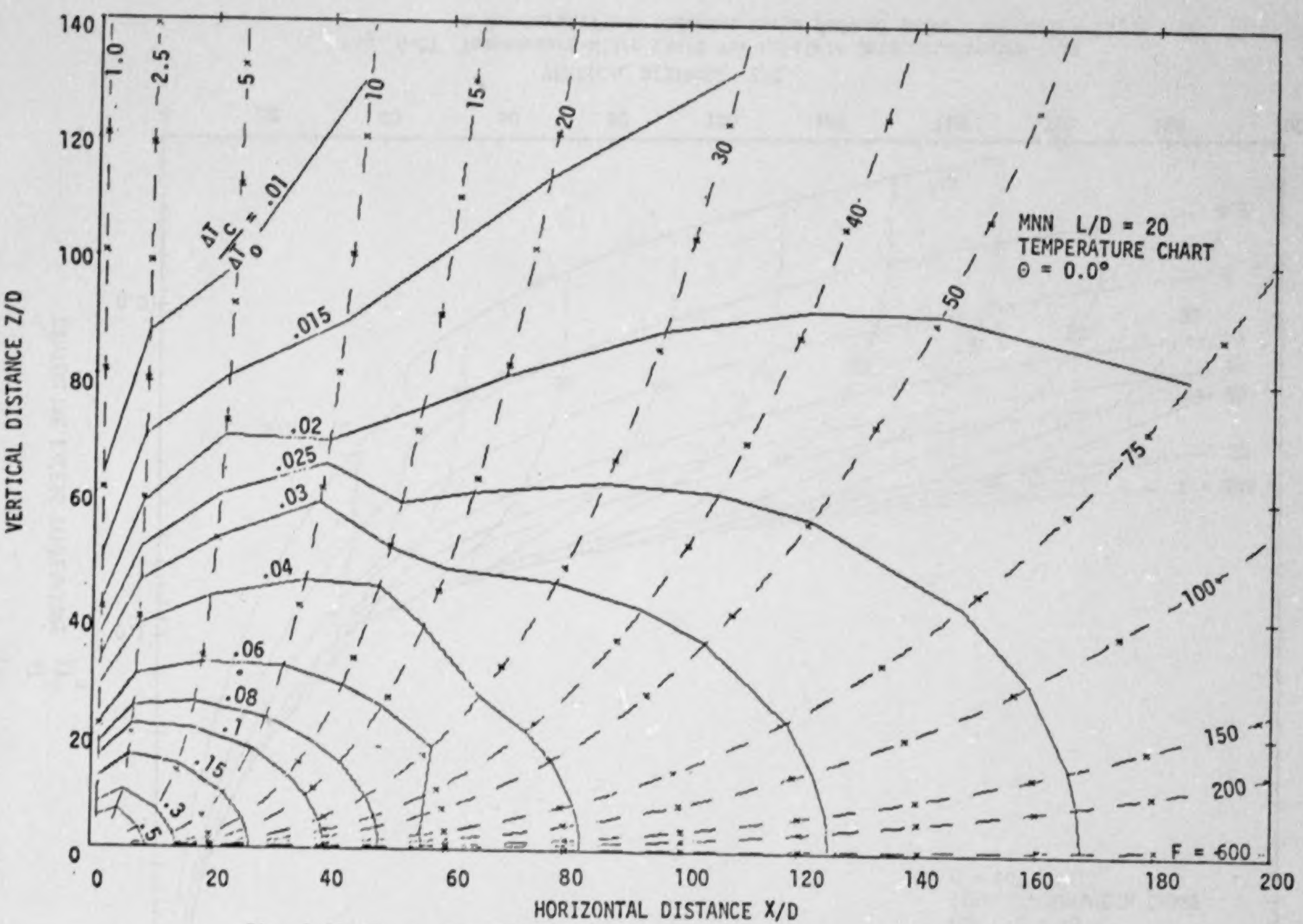

Fig. A-22 Temperature-Trajectory Chart for Multiple Jets Discharging into a Non-Stratified, Stagnant Body of Water: MNN L/D = 20, Θ = 0°

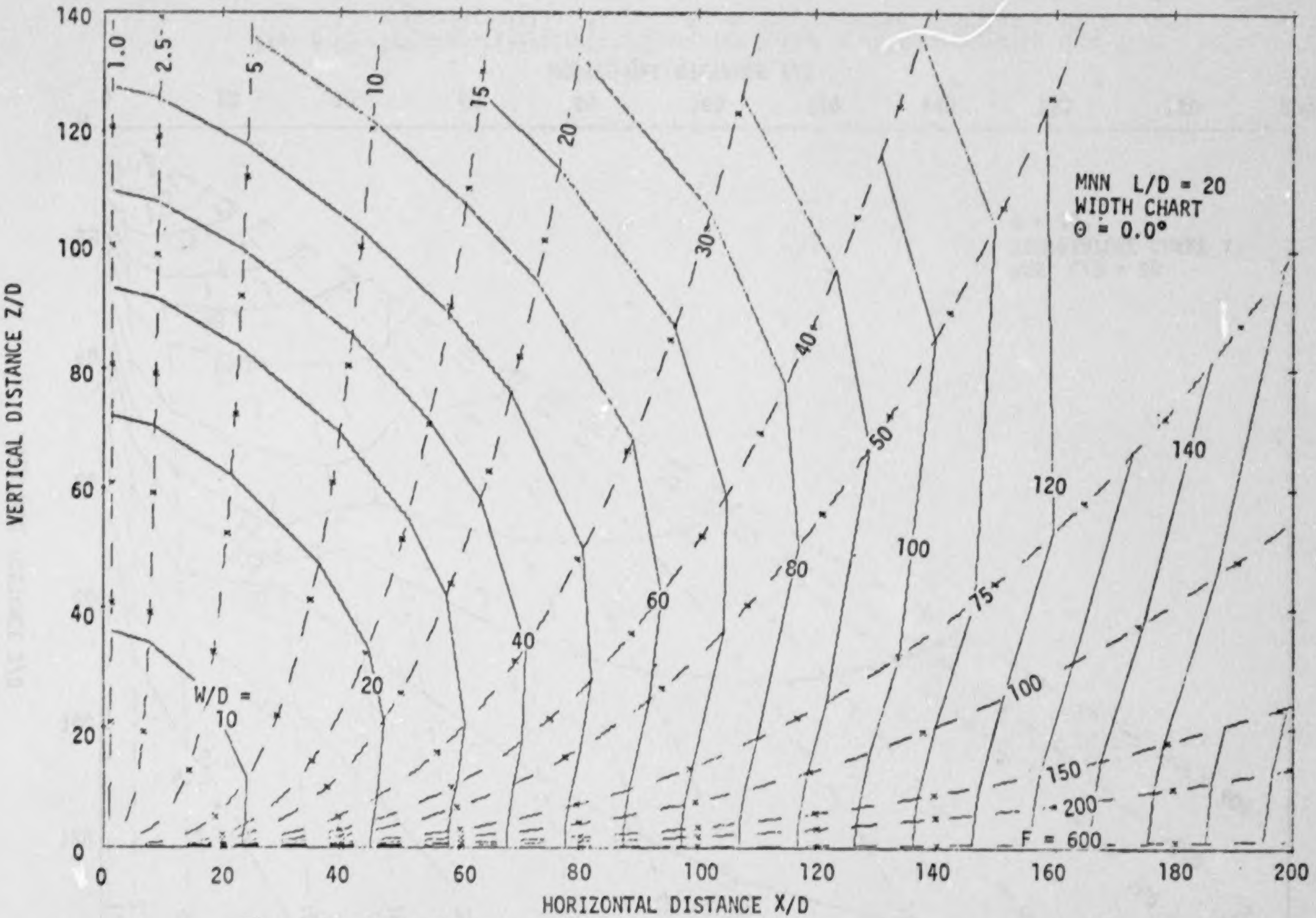

Fig. A-23 Width-Trajectory Chart for Multiple Jets Discharging into a Non-Stratified, Stagnant Large Body of Water: MNN L/D = 20, Θ = 0°

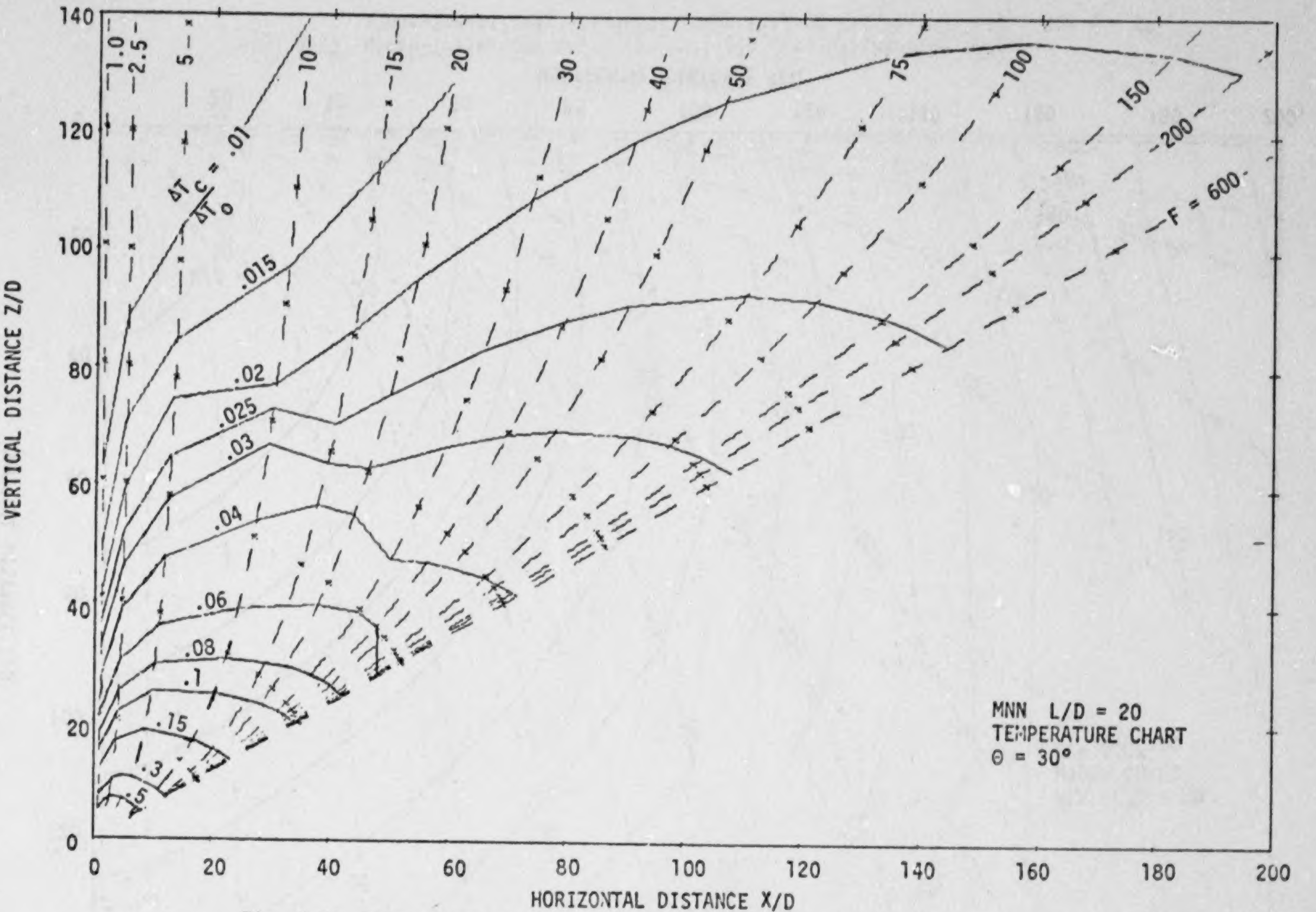

Fig. A-24 Temperature-Trajectory Chart for Multiple Jets Discharging into a Non-Stratified, Stagnant Large Body of Water: MNN L/D = 20, Θ = 30°

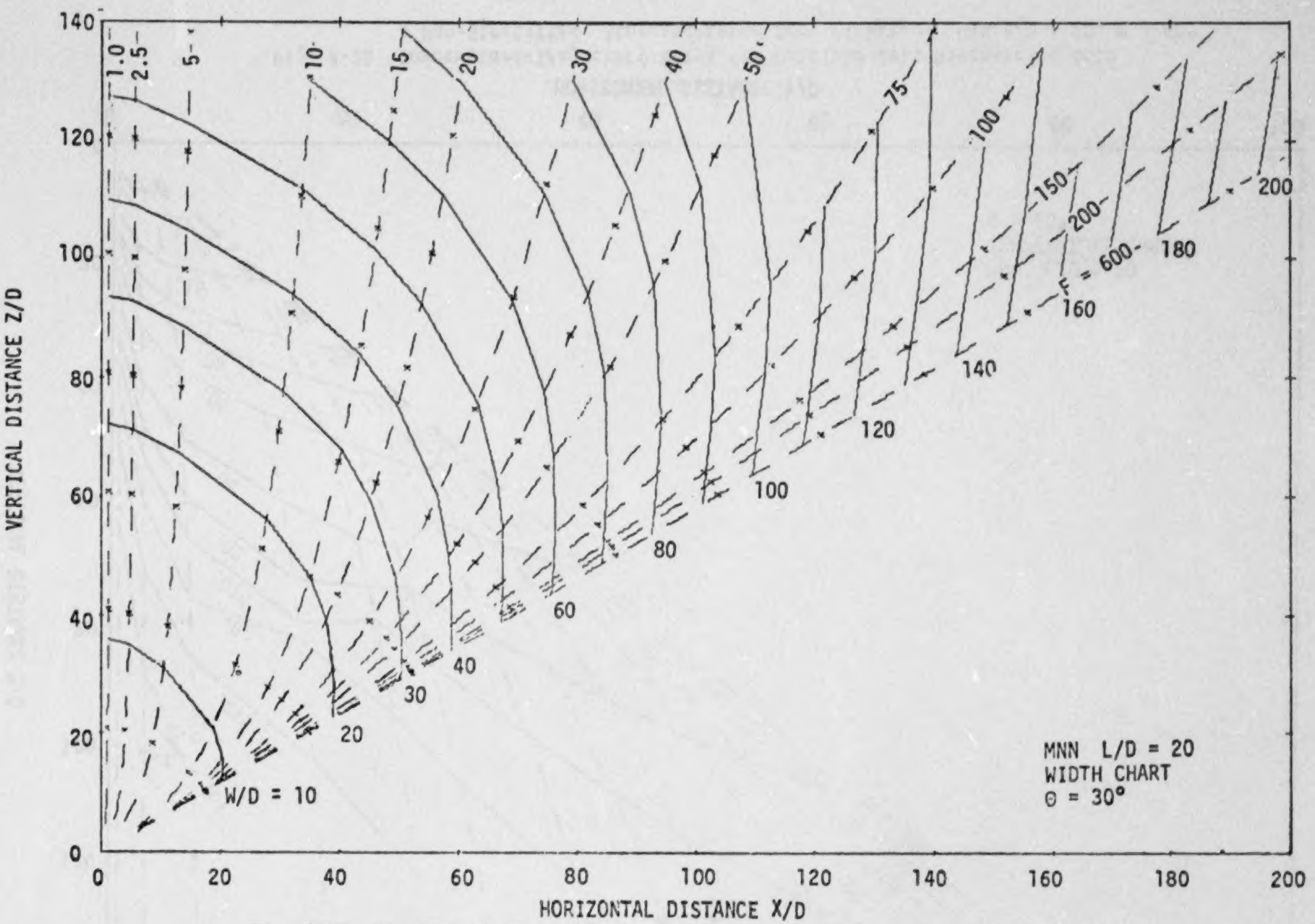

Fig. A-25 Width-Trajectory Chart for Multiple Jets Discharging into a Non-Stratified, Stagnant Large Body of Water: MNN L/D = 20, Θ = 30°

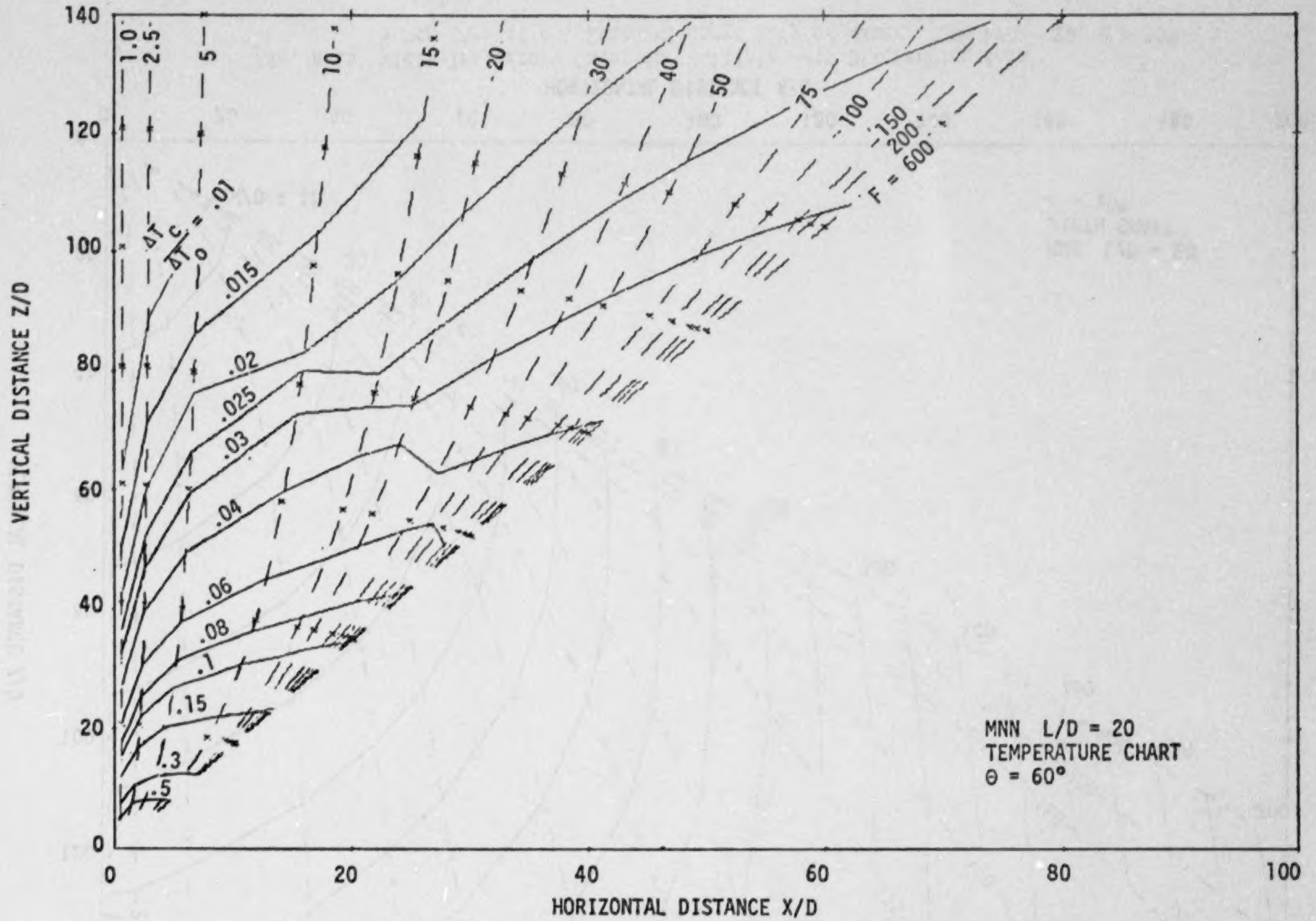

Fig. A-26 Temperature-Trajectory Chart for Multiple Jets Discharging into a Non-Stratified, Stagnant Large Body of Water: MNN L/D = 20, Θ = 60°

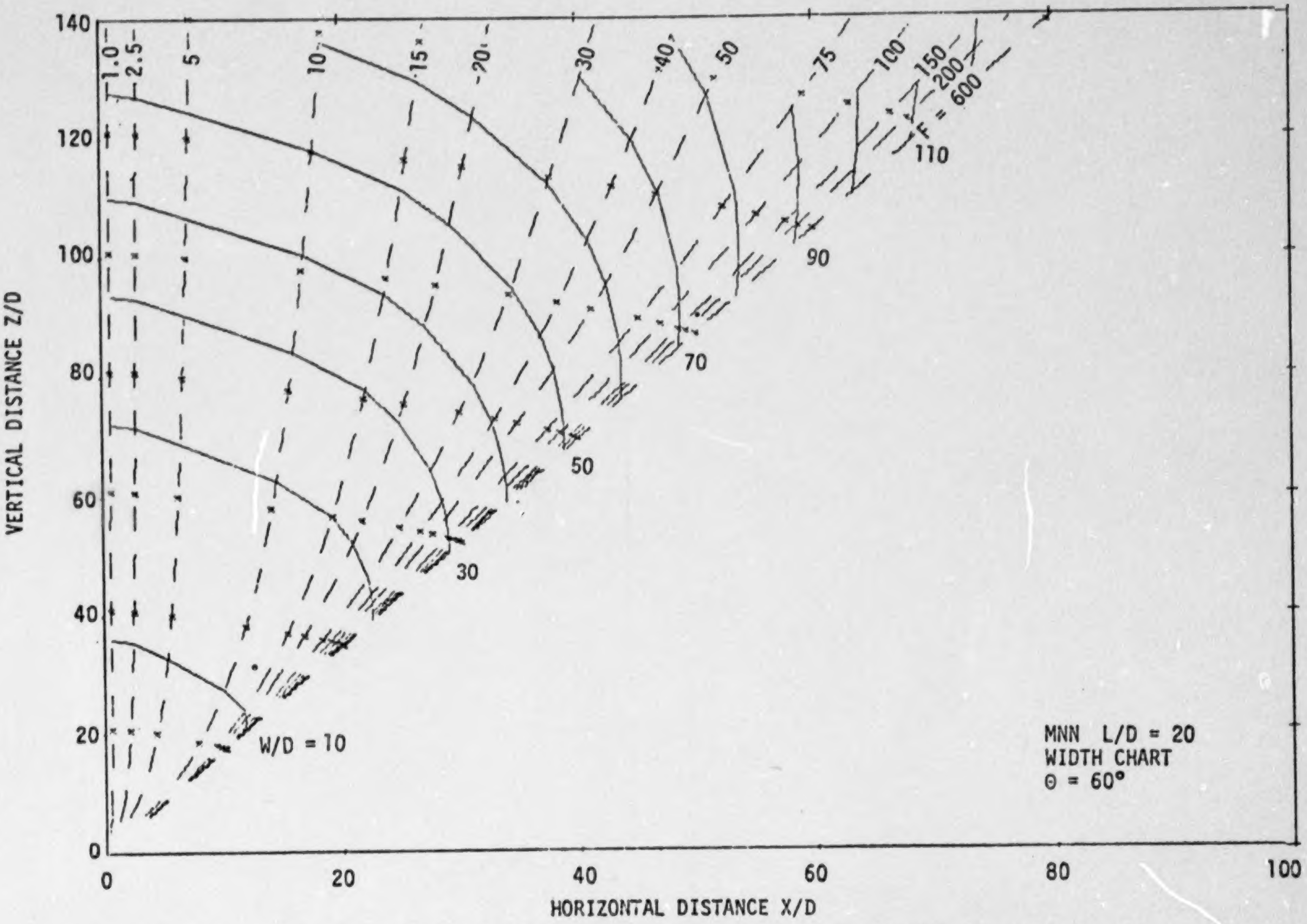

Fig. A-27 Width-Trajectory Chart for Multiple Jets Discharging into a Non-Stratified, Stagnant Large Body of Water: MNN L/D = 20, Θ = 60°

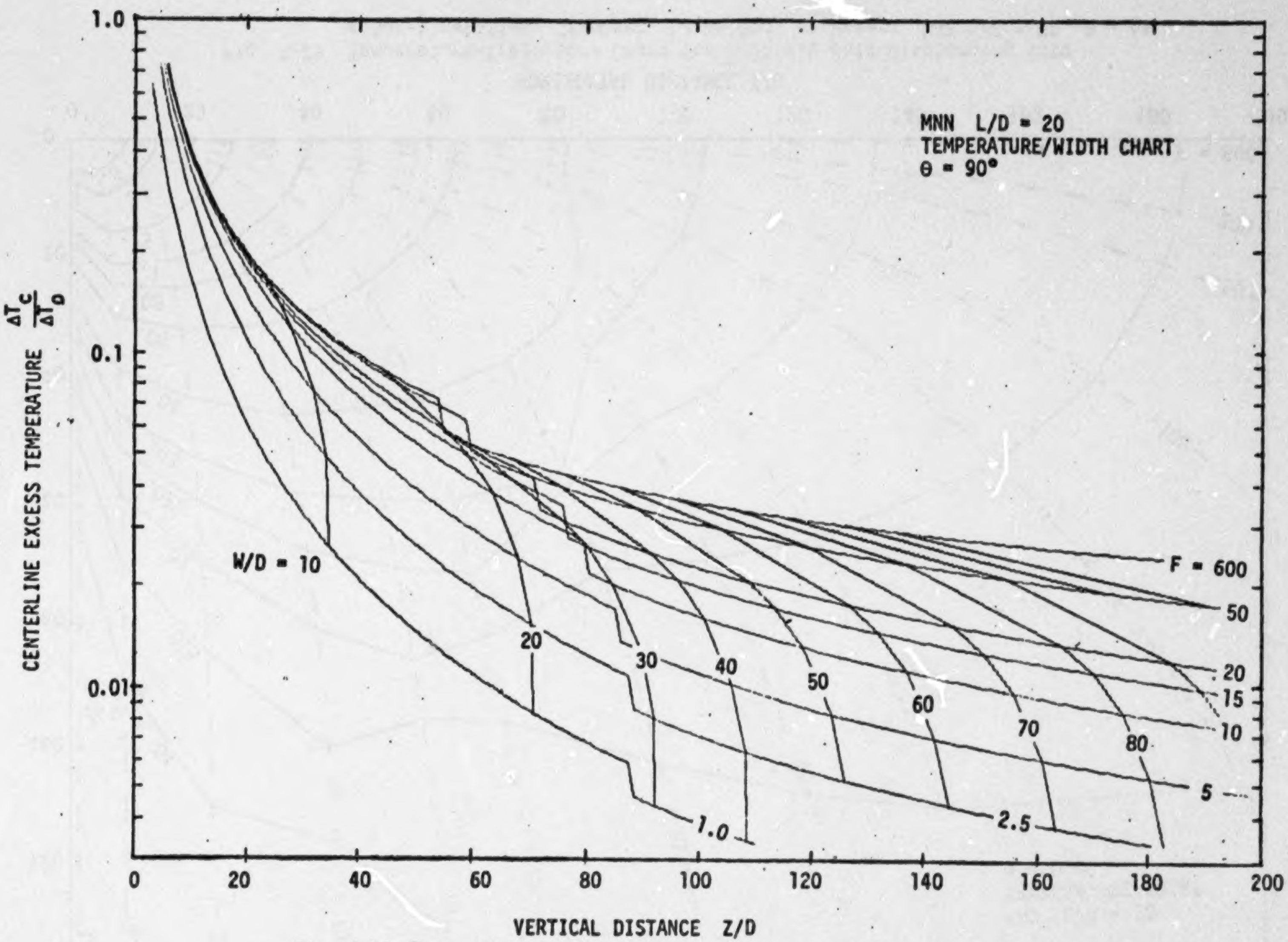

Fig. A-28 Temperature-Width Chart for Multiple Jets Discharging into a Non-Stratified, Stagnant, Large Body of Water: MNN L/D = 20, θ = 90°

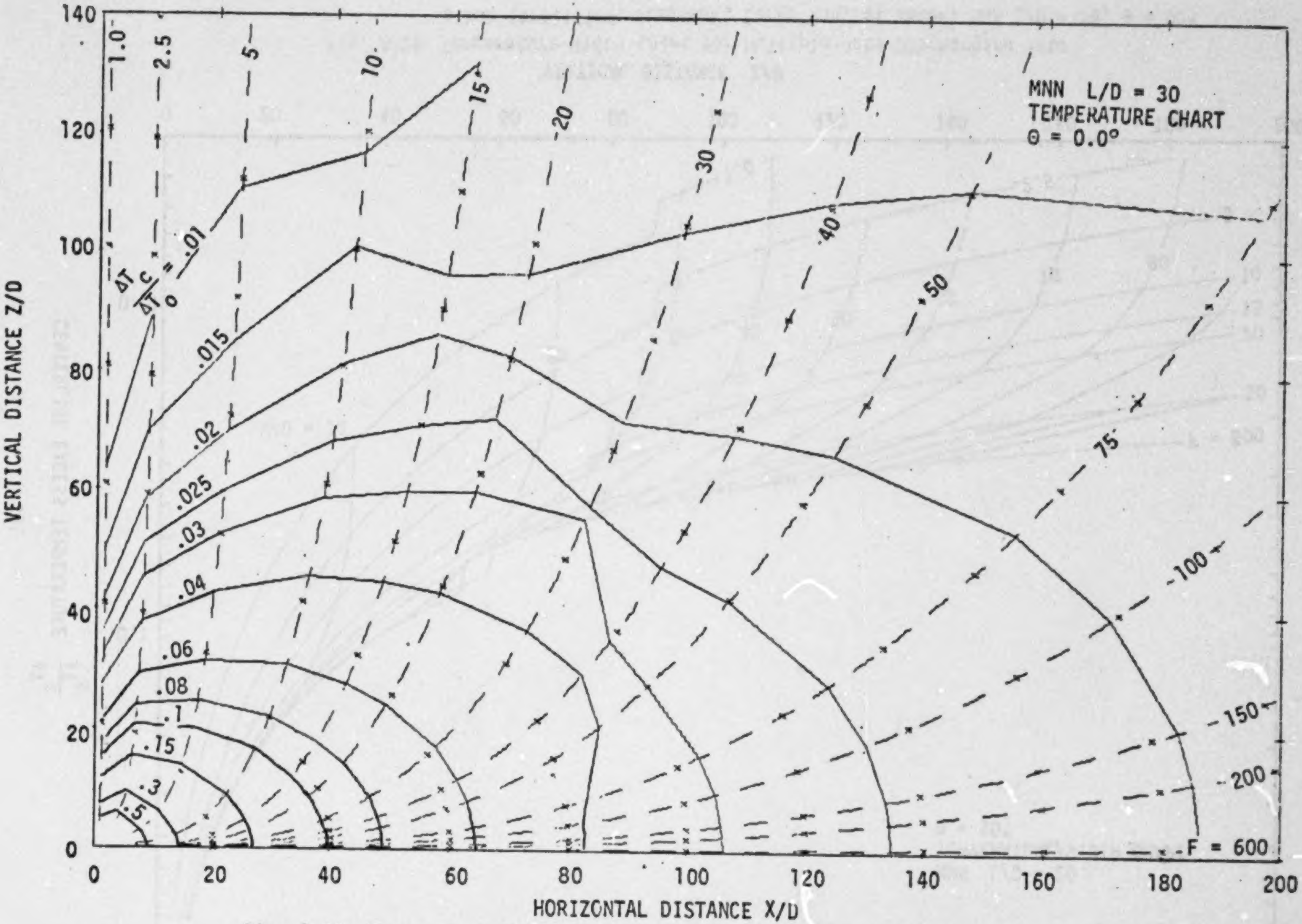

Fig. A-29 Temperature-Trajectory Chart for Multiple Jets Discharging into a Non-Stratified, Stagnant, Large Body of Water: MNN L/D = 30, Θ = 0°

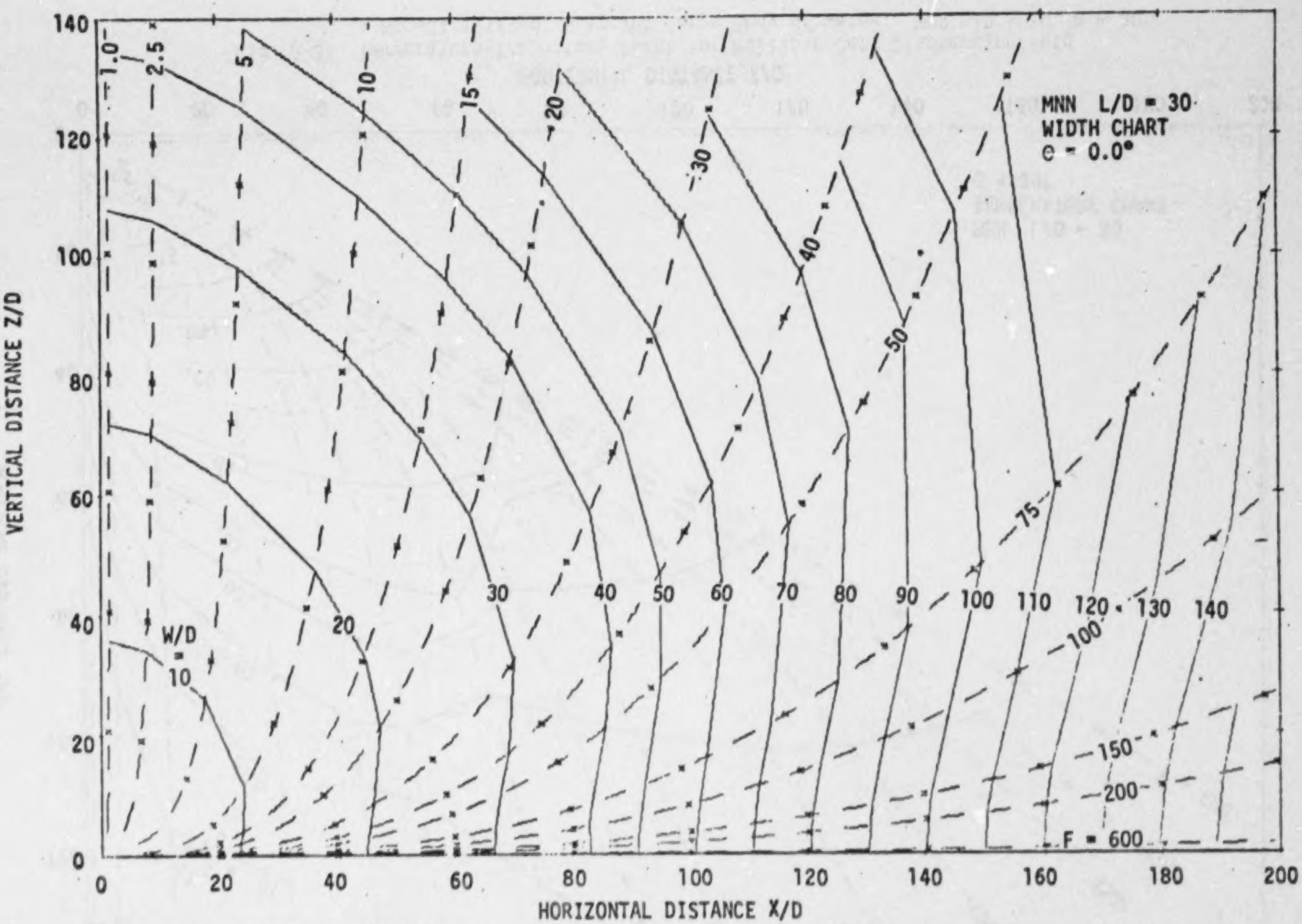

Fig. A-30 Width-Trajectory Chart for Multiple Jets Discharging into a Non-Stratified, Stagnant Large Body of Water: MNN L/D = 30, Θ = 0°

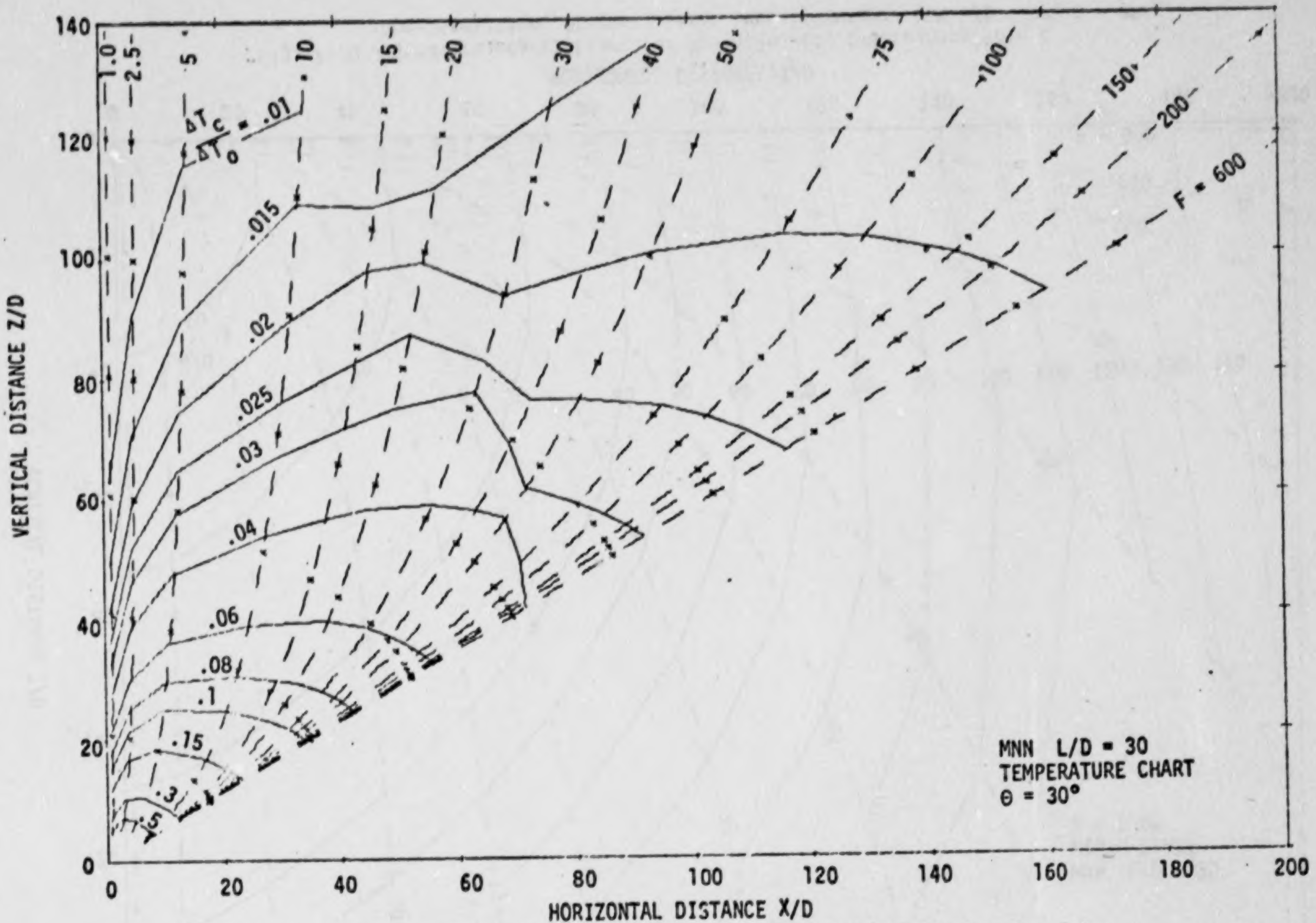

Fig. A-31 Temperature-Trajectory Chart for Multiple Jets Discharging into a Non-Stratified, Stagnant Large Body of Water: MNN L/D = 30, Θ = 30°

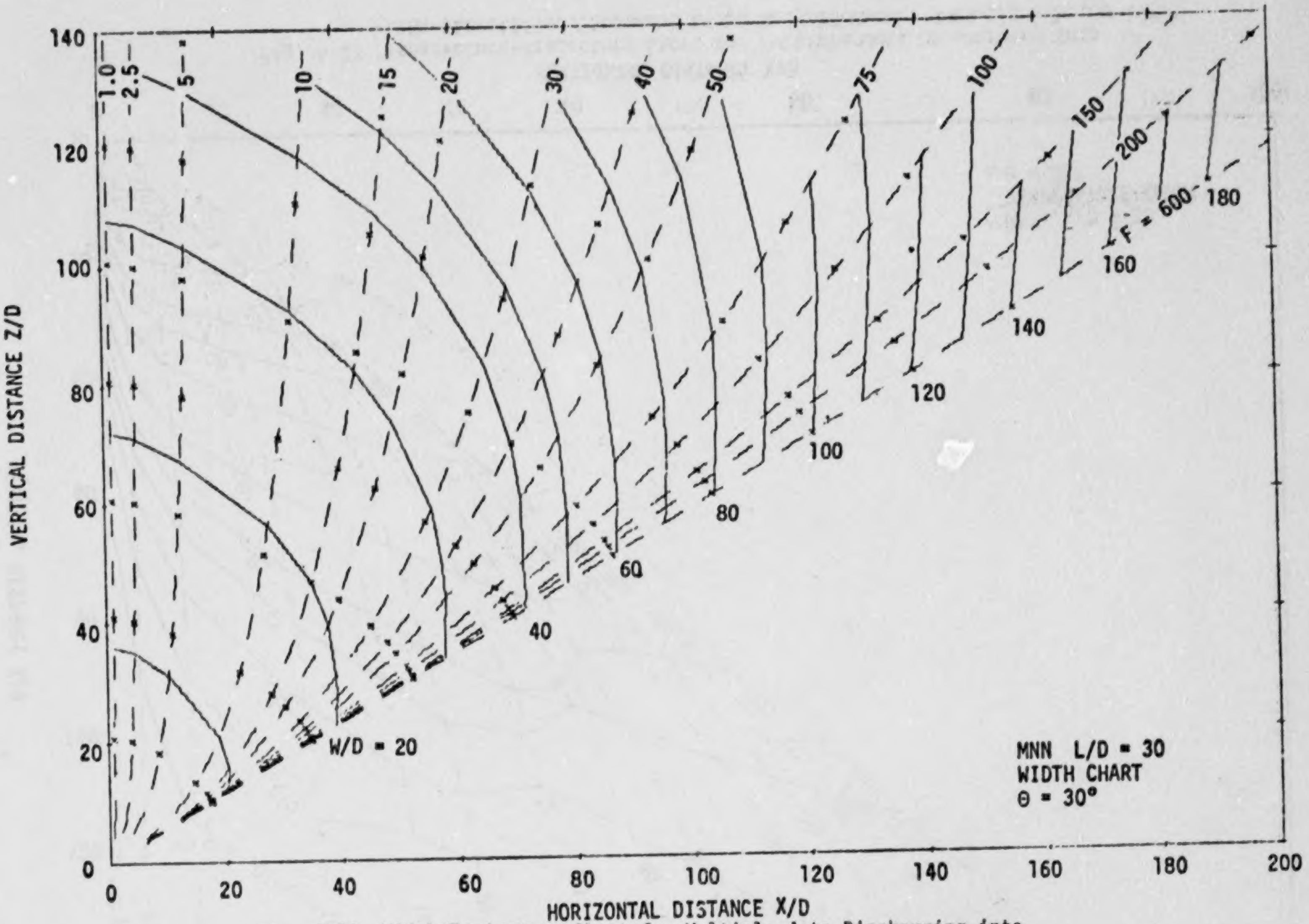

Fig. A-32 Width-Trajectory Chart for Multiple Jets Discharging into a Non-Stratified, Stagnant Large Body of Water: MNN L/D = 30, Θ= 30°

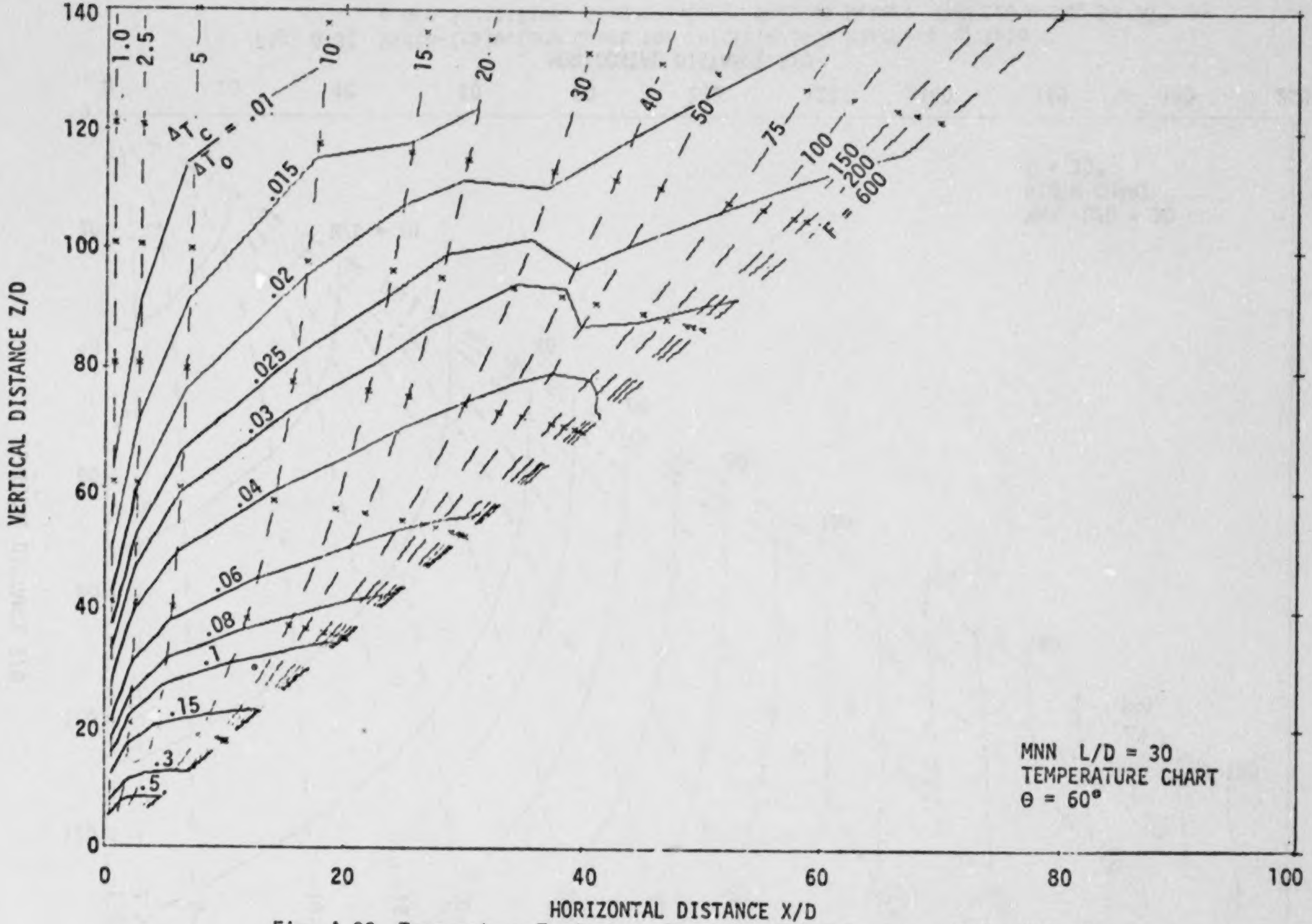

Fig. A-33 Temperature-Trajectory Chart for Multiple Jets Discharging into a Non-Stratified, Stagnant Large Body of Water: MNN L/D = 30, θ = 60°

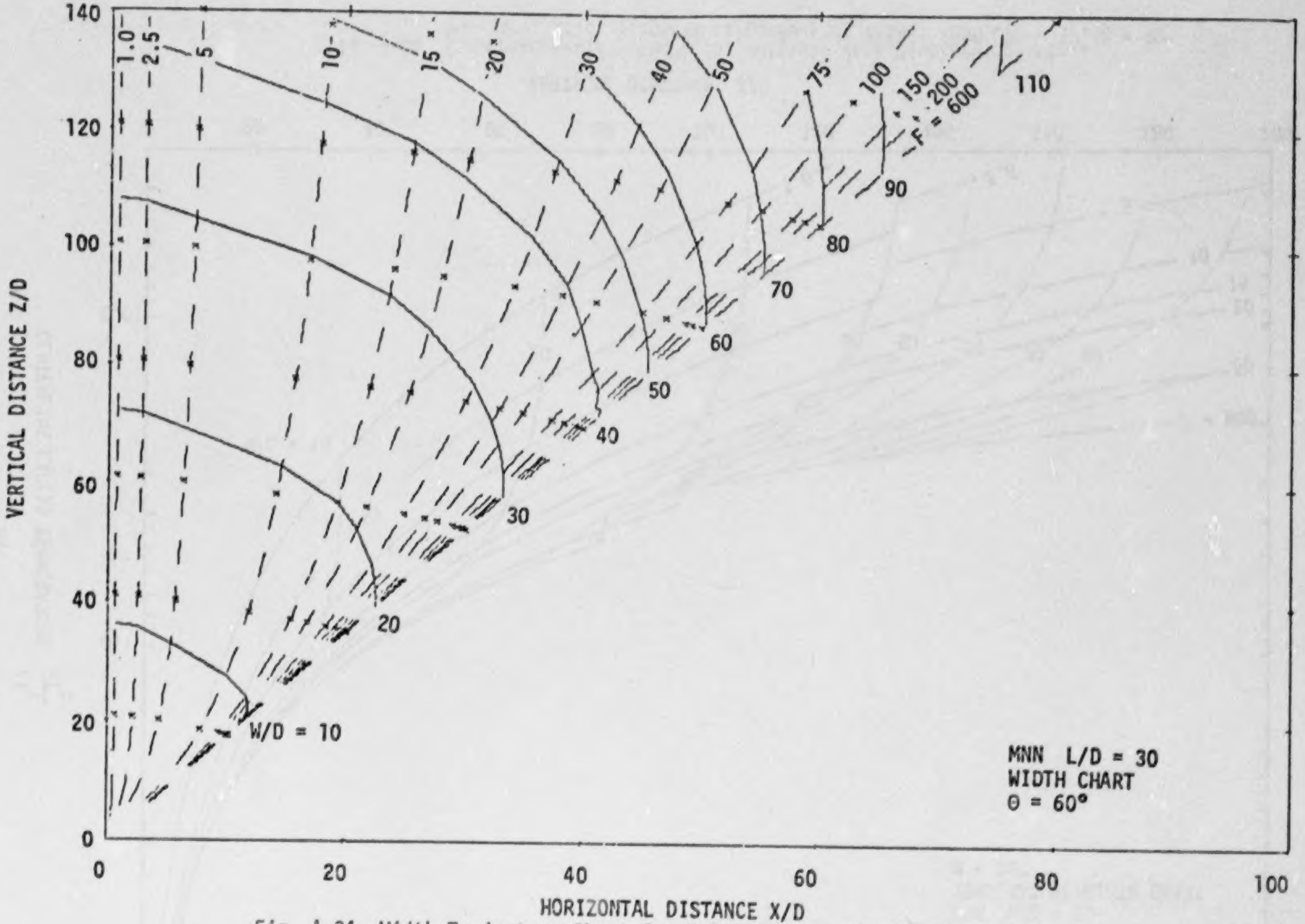

Fig. A-34 Width-Trajectory Chart for Multiple Jets Discharging into a Non-Stratified, Stagrant Large Body of Water: MNN L/D = 30, θ = 50°

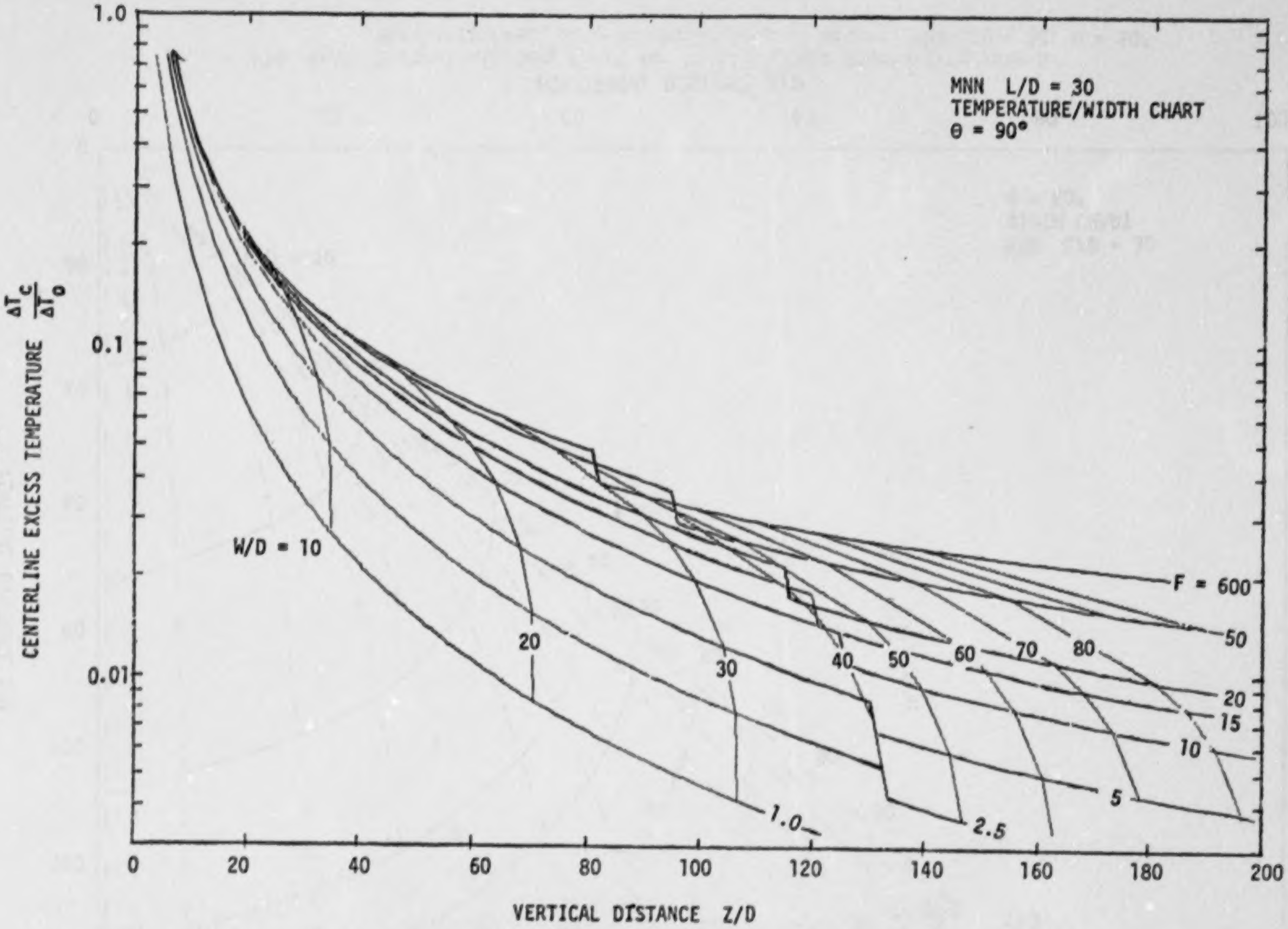

Fig. A-35 Temperature-Width Chart for Multiple Jets Discharging into a Non-Stratified, Stagnant Large Body of Water: MNN L/D = 30, θ = 90°

APPENDIX B

Nomograms for Discharge into Stagnant, Stratified Water, (RNS, MNS)

TABLE II

Figure Numbers Corresponding to Plume Behavior From Submerged Diffusers Discharging into a Stagnant, Stratified Ambient Water

Diffuser	$Z_s/D = 0$				$Z_s/D = 10$				$Z_s/D = 30$			
	$\Theta=0°$	$\Theta=30°$	$\Theta=60°$	$\Theta=90°$	$\Theta=0°$	$\Theta=30°$	$\Theta=60°$	$\Theta=90°$	$\Theta=0°$	$\Theta=30°$	$\Theta=60°$	$\Theta=90°$
RNS	B- 1	B- 2	B- 3	B- 4	B- 5	B- 6	B- 7	B- 8	B-9	B-10	B-11	B-12
MNS $L/D=1.5$	B-13	B-14	B-15	B-16	B-17	B-18	B-19	B-20	B-21	B-22	B-23	B-24
MNS $L/D=10$	B-25	B-26	B-27	B-28	B-29	B-30	B-31	B-32	B-33	B-34	B-35	B-36
MNS $L/D=20$	B-37	B-38	B-39	B-40	B-41	B-42	B-43	B-44	B-45	B-46	B-47	B-48

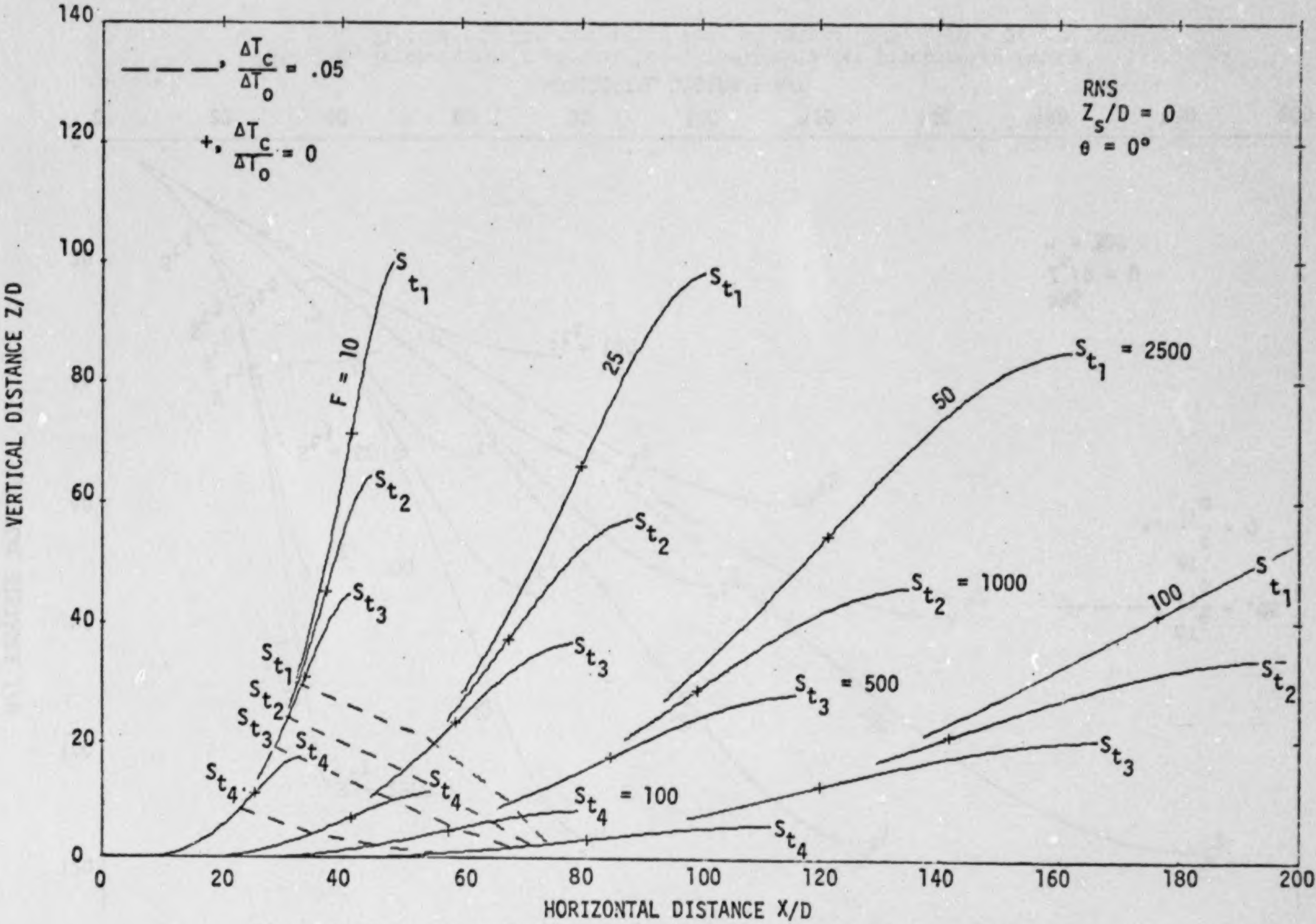

Fig. B-1 Temperature-Trajectory Chart for Single Jet Discharging into a Stratified, Stagnant Large Body of Water: RNS, $Z_s/D = 0$, $\Theta = 0°$

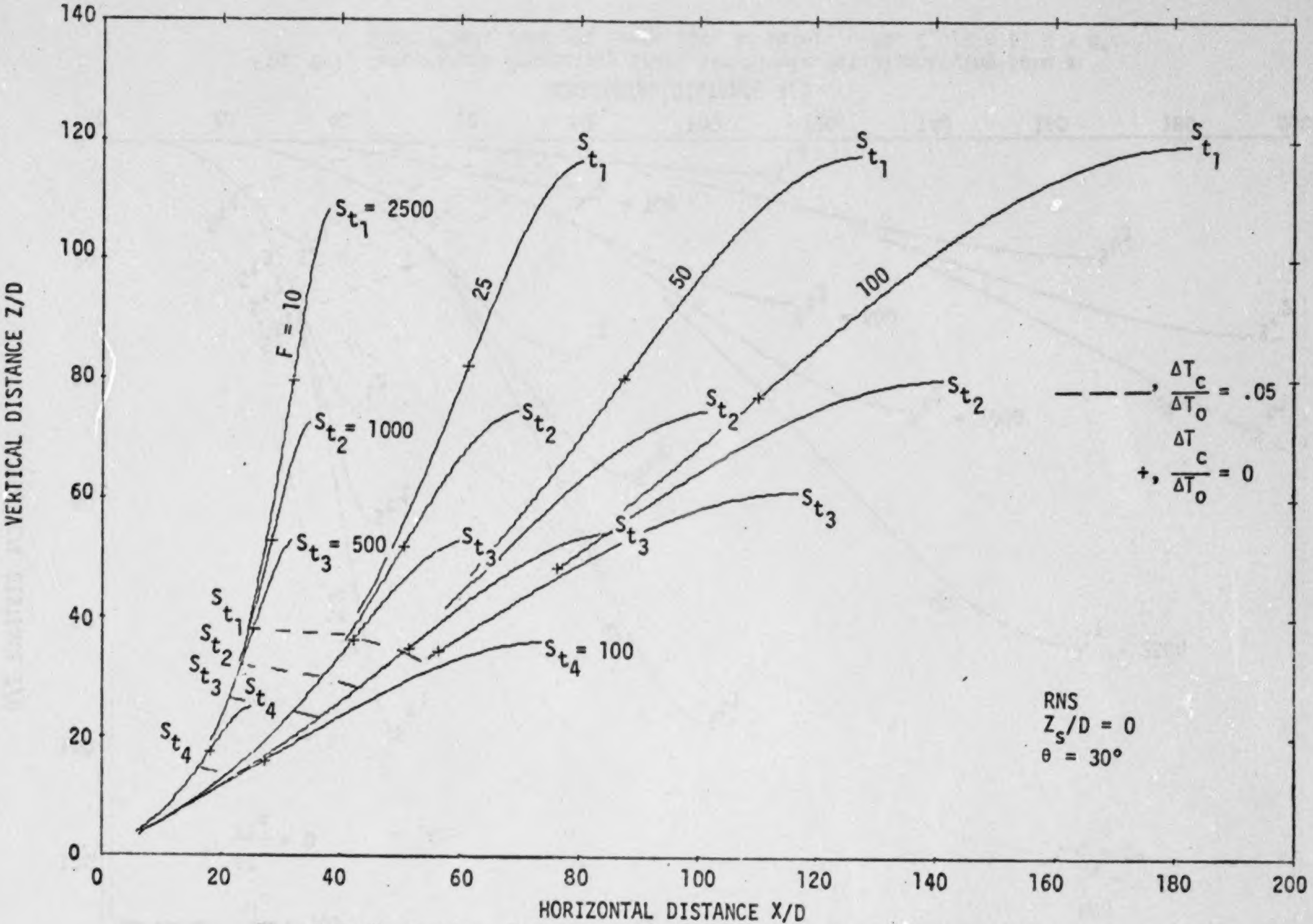

Fig. B-2 Temperature-Trajectory Chart for Single Jet Discharging into a Stratified, Stagnant Large Body of Water: RNS, $Z_s/D = 0$, $\Theta = 30°$

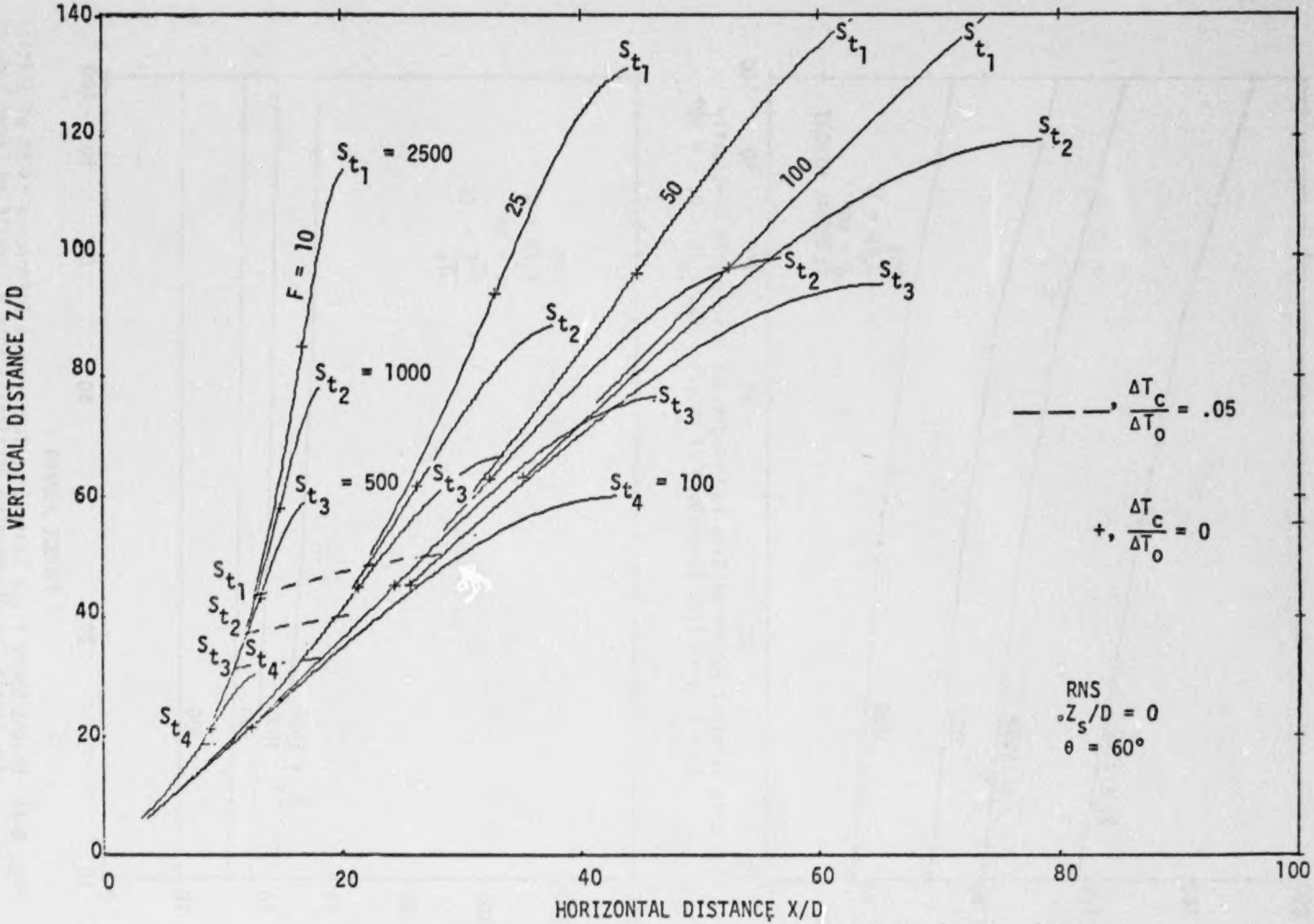

Fig. B-3 Temperature-Trajectory Chart for Single Jet Discharging into a Stratified, Stagnant Large Body of Water: RNS, $Z_s/D = 0$, $\Theta = 60°$

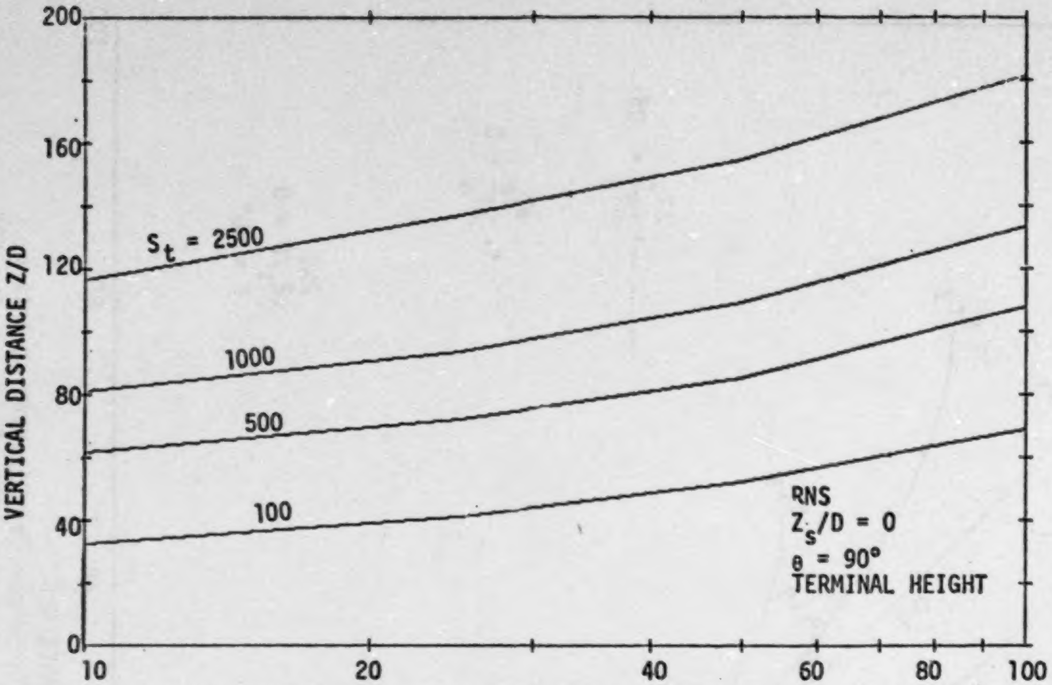

Fig. B-4a Terminal Height of Rise for Single Jet Discharging Vertically into a Stratified Large Body of Water: RNS, $Z_s/D = 0$, Θ = 90°

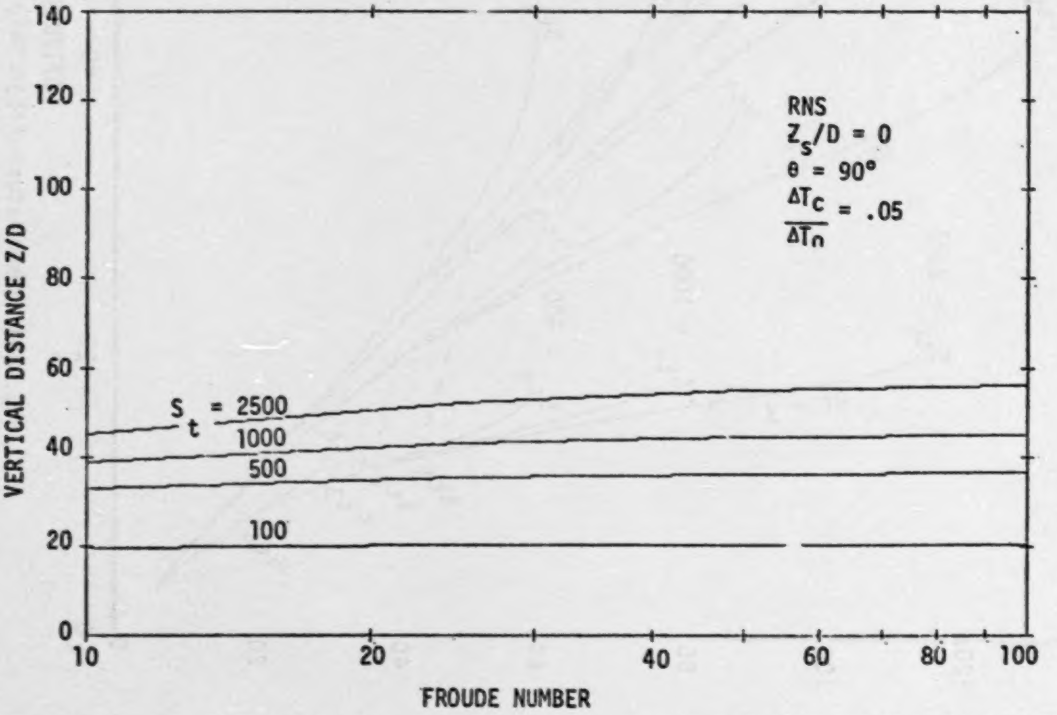

Fig. B-4b Height Where Plume Centerline Temperature Difference is 5% of Initial for Single Jet Discharging Vertically into a Stratified Large Body of Water: RNS, $Z_s/D = 0$, Θ = 90°

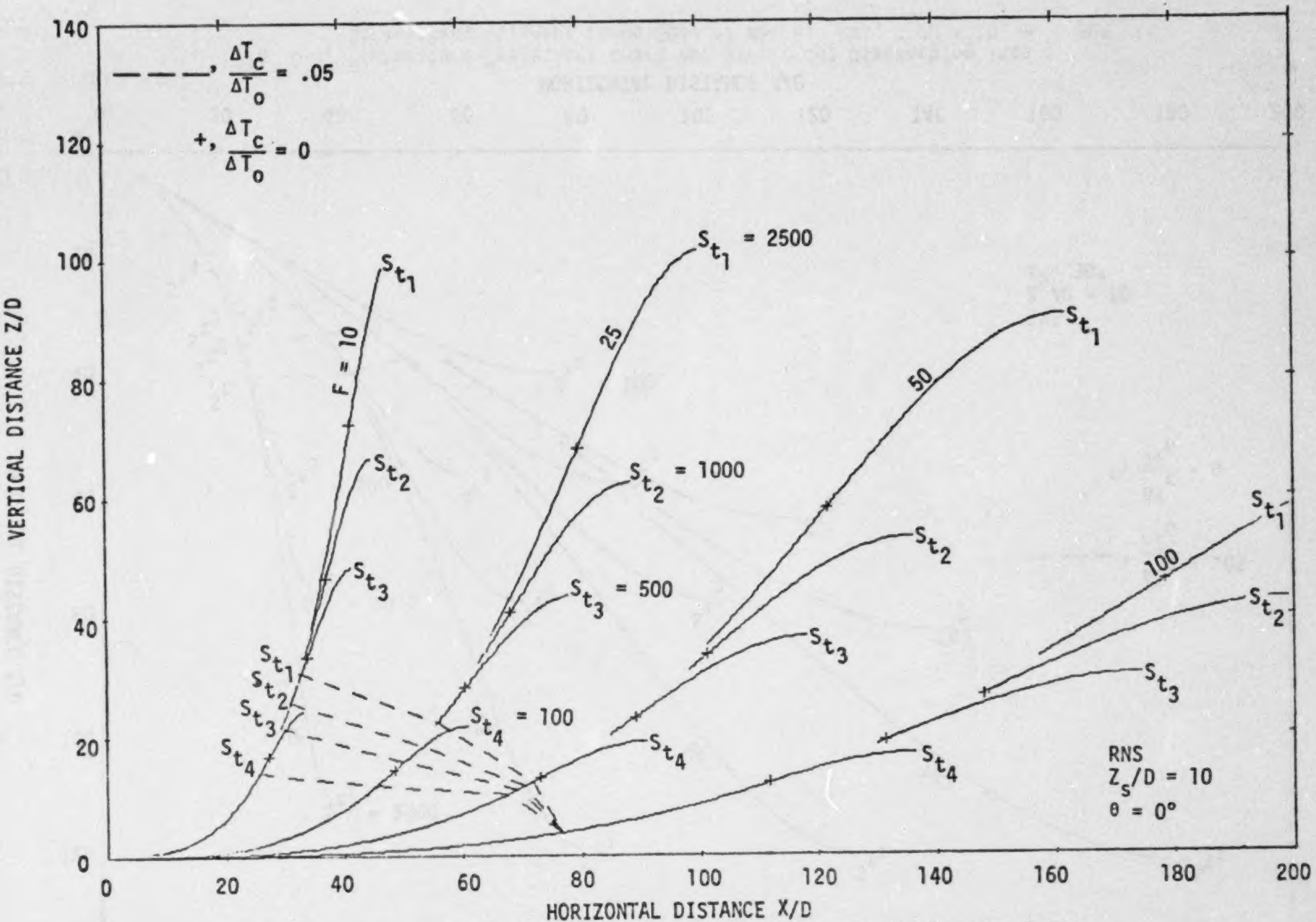

Fig. B-5 Temperature-Trajectory Chart for Single Jet Discharging into a Stratified, Stagnant Large Body of Water: RNS, $Z_s/D = 10$, $\Theta = 0°$

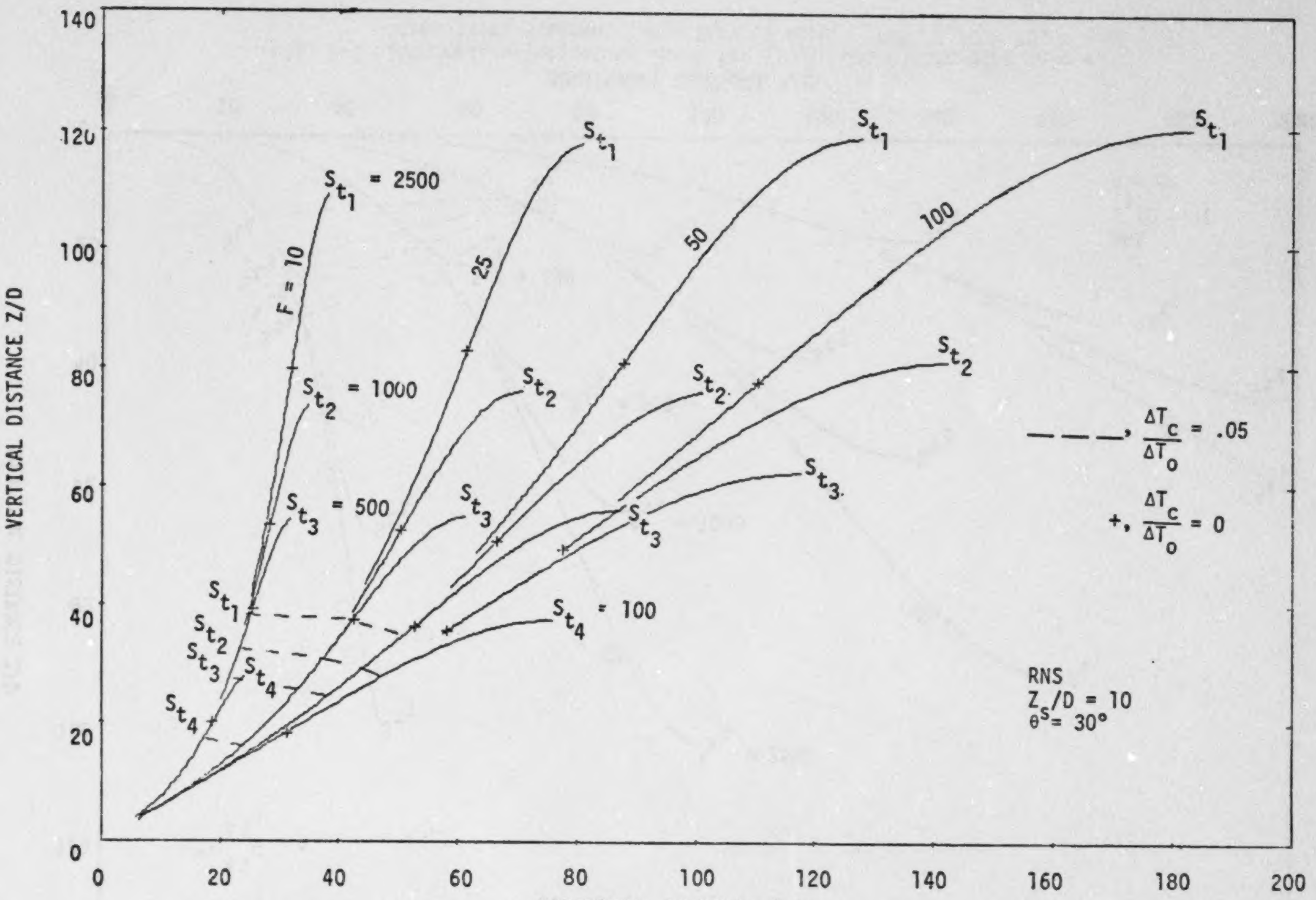

Fig. B-6 Temperature-Trajectory Chart for Single Jet Discharging into a Stratified, Stagnant Large Body of Water: RNS, $Z_s/D = 10$, $\Theta = 30°$

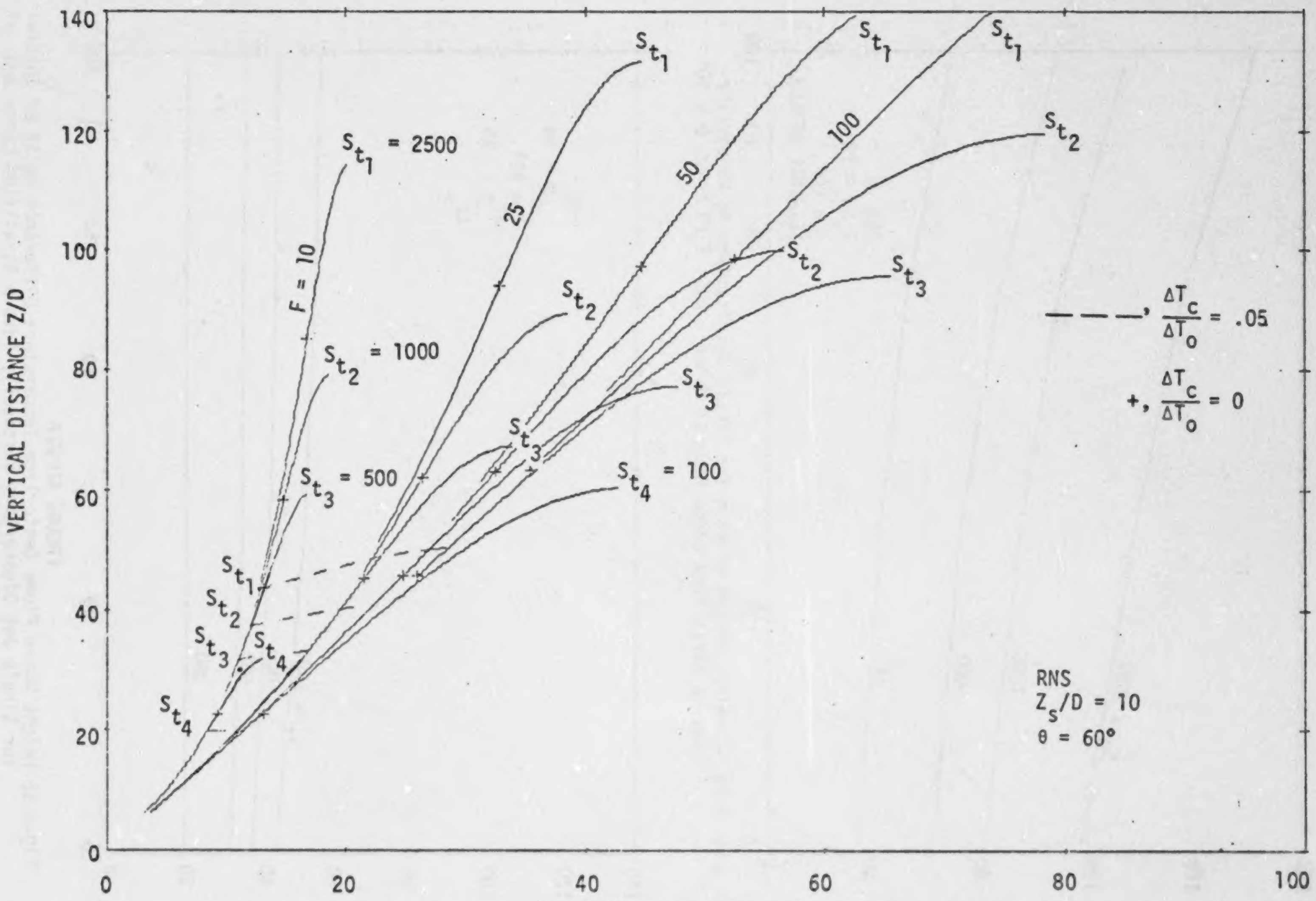

Fig. B-7 Temperature-Trajectory Chart for Single Jet Discharging into a Stratified, Stagnant Large Body of Water: RNS, $Z_s/D = 10$, $\Theta = 60°$

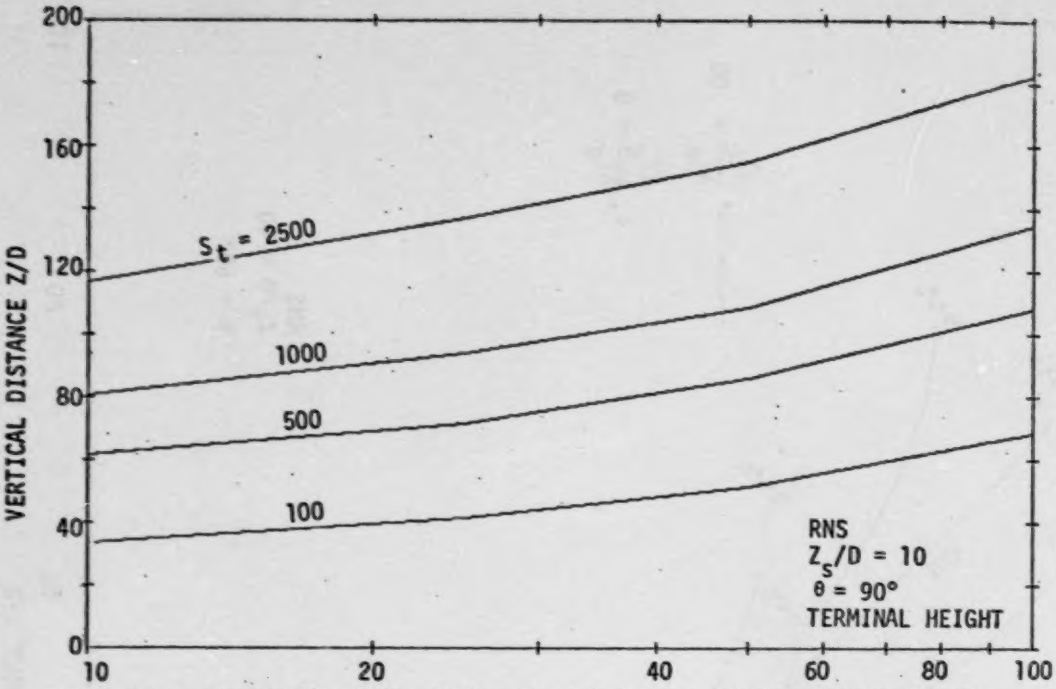

Fig. B-8a Terminal Height of Rise for Single Jet Discharging Vertically into a Stratified Large Body of Water: RNS, $Z_s/D = 10$, $\Theta = 90°$

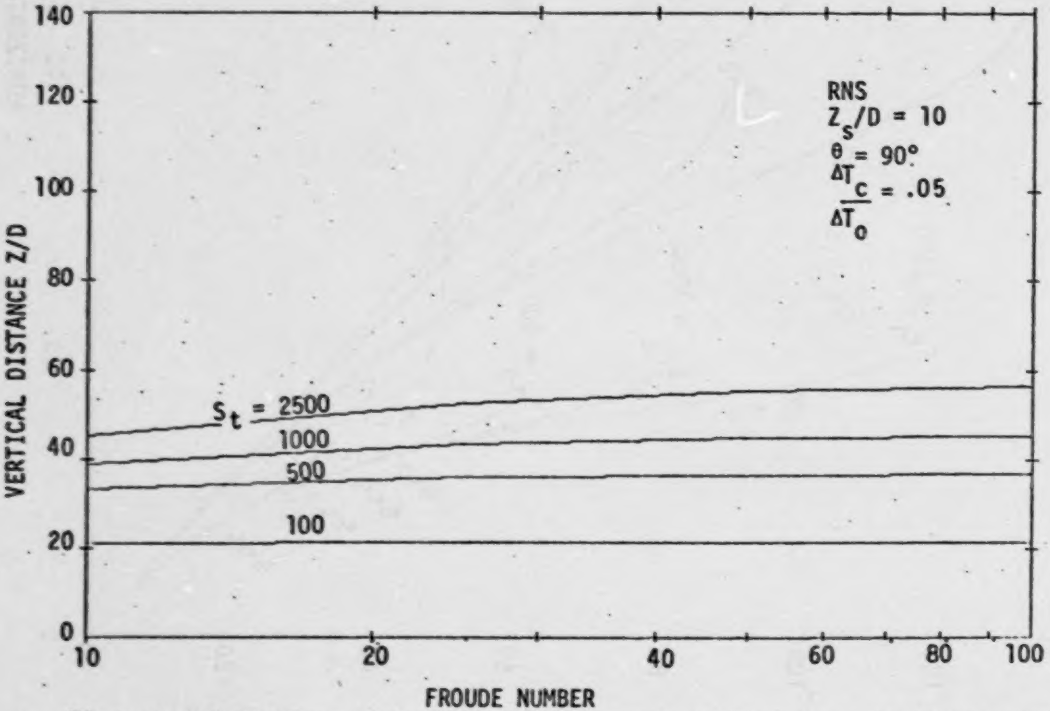

Fig.B-8b Height Where Plume Centerline Temperature Difference is 5% of Initial for Single Jet Discharging Vertically into a Stratified Large Body of Water: RNS, $Z_s/D = 10$, $\Theta = 90°$

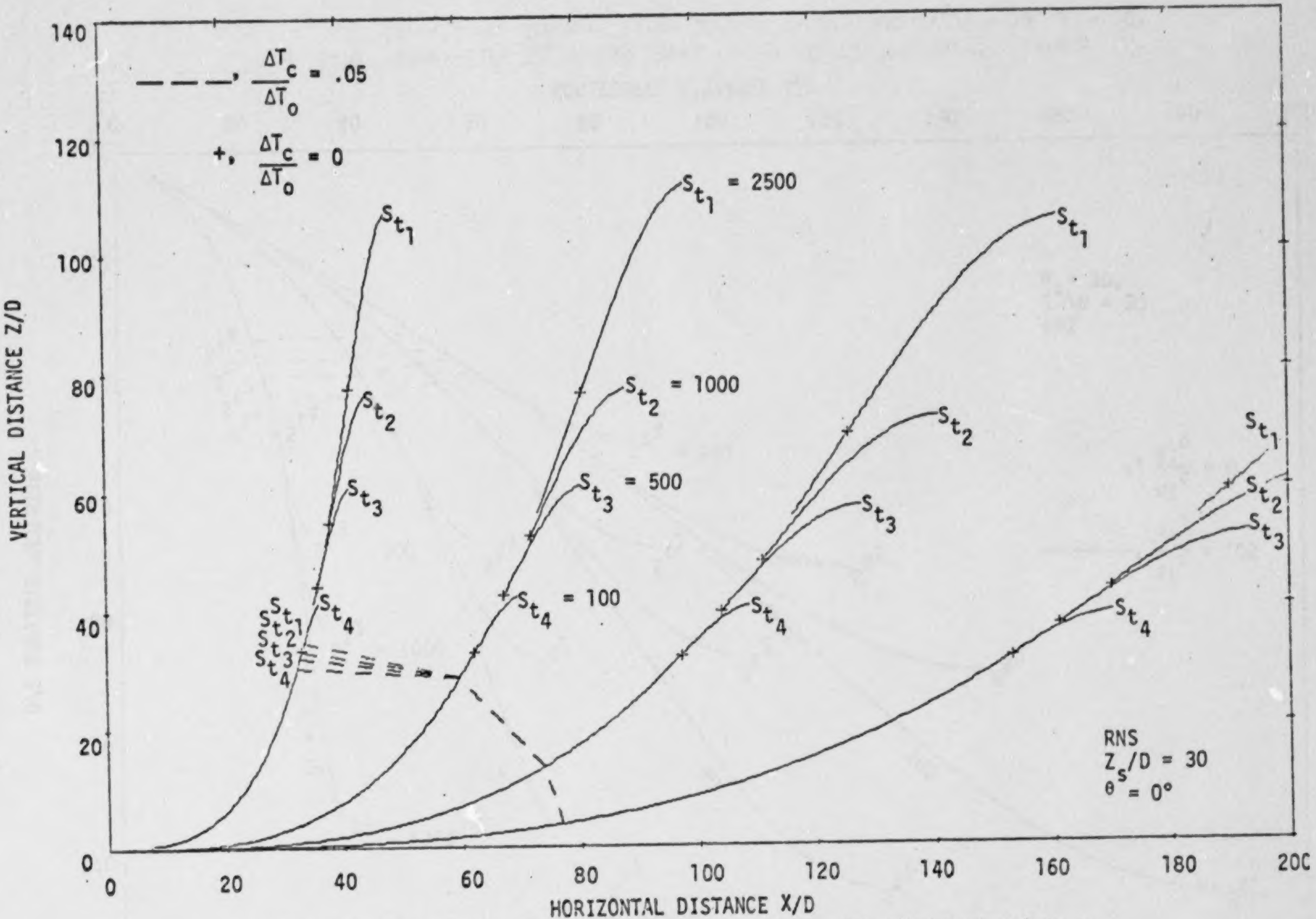

Fig. B-9 Temperature-Trajectory Chart for Single Jet Discharging into a Stratified, Stagnant Large Body of Water: RNS, $Z_s/D = 30$, $\Theta = 0°$

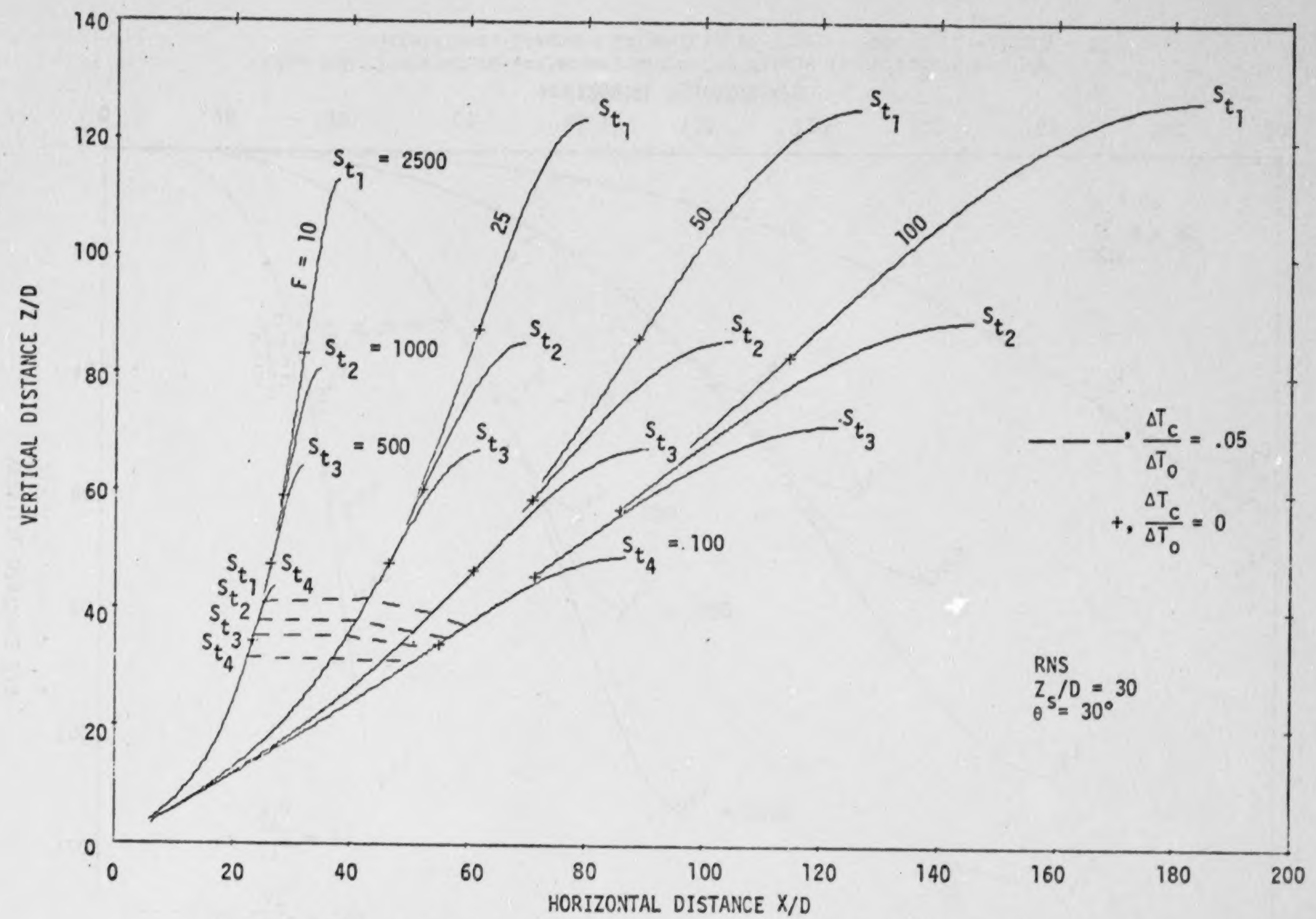

Fig. B-10 Temperature-Trajectory Chart for Single Jet Discharging into a Stratified, Stagnant Large Body of Water: RNS, $Z_s/D = 30$, $\Theta = 30°$

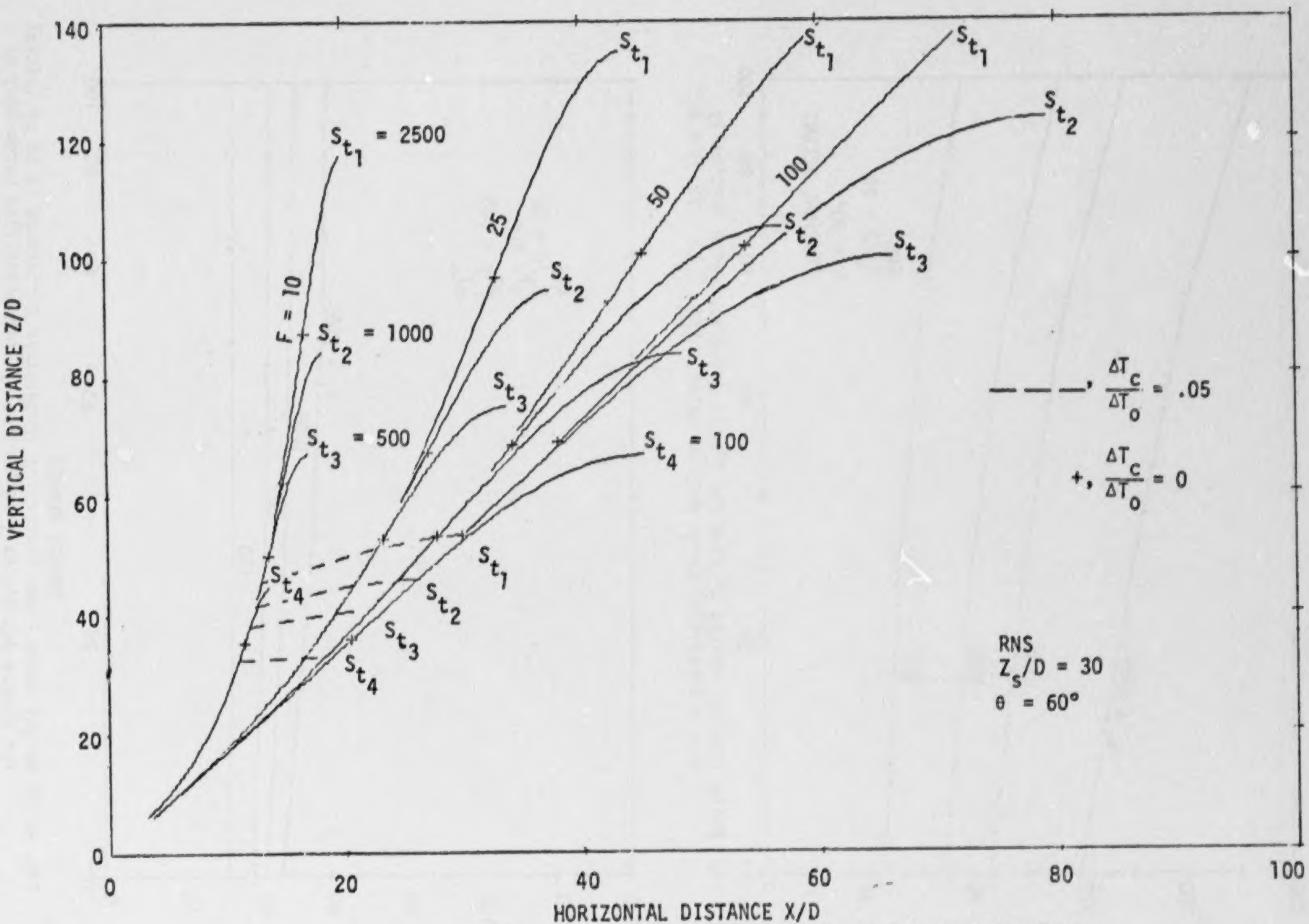

Fig. B-11 Temperature-Trajectory Chart for a Single Jet Discharging into a Stratified, Stagnant Large Body of Water: RNS, Z_s/D = 30, Θ = 60°

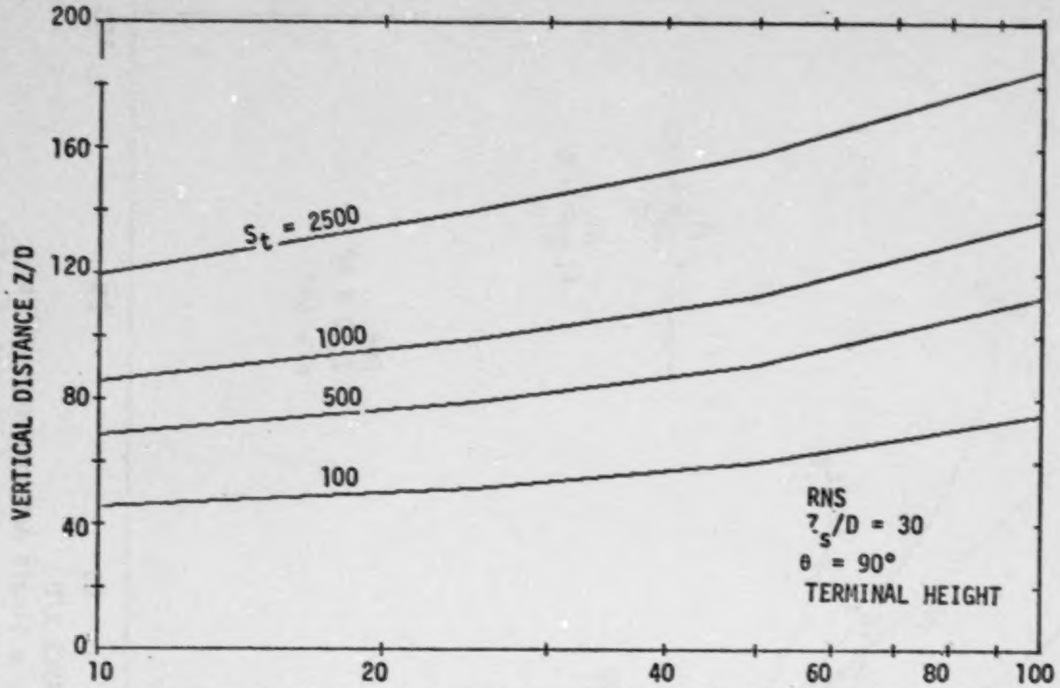

Fig. B-12a Terminal Height of Rise for Single Jet Discharging Vertically into a Stratified Large Body of Water: RNS, $Z_s/D = 30$, $\Theta = 90°$

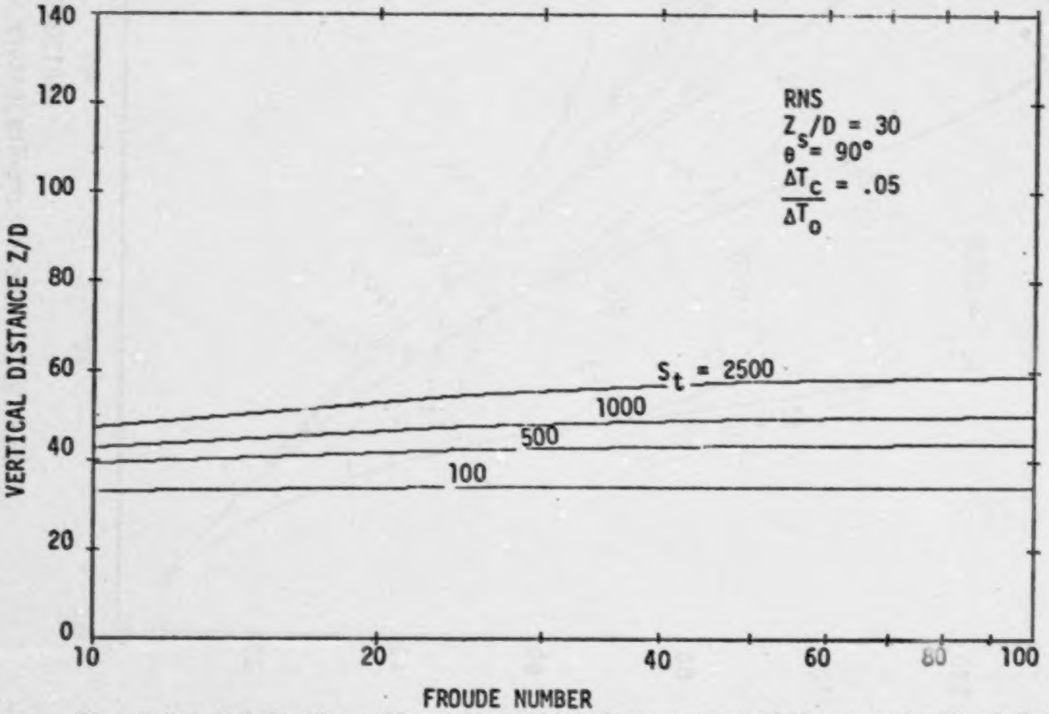

Fig. B-12b Height Where Plume Centerline Temperature Difference is 5% of Initial for Single Jet Discharging Vertically into Stratified Large Body of Water: RNS, $Z_s/D = 30$, $\Theta = 90°$

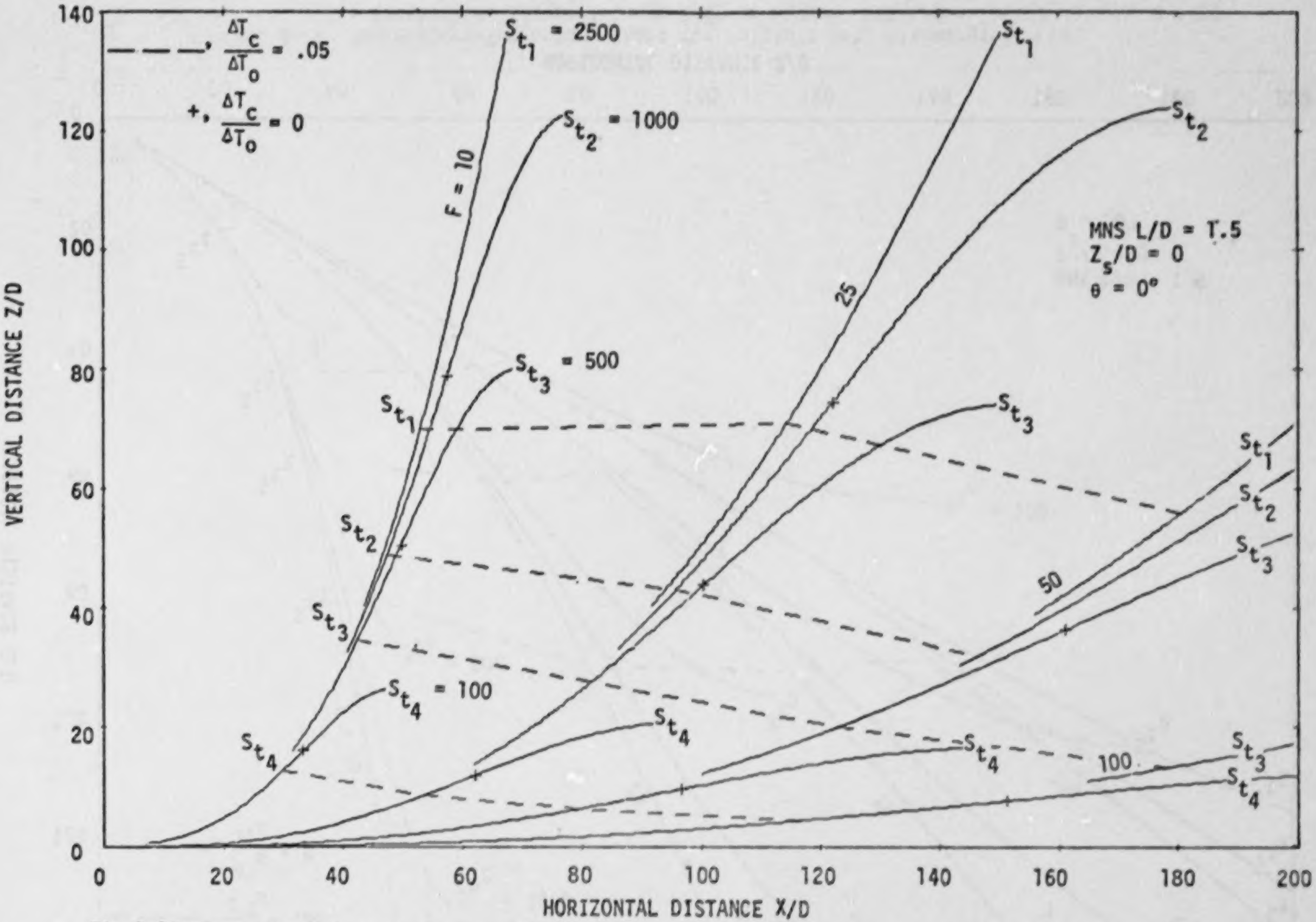

Fig.B-13 Temperature-Trajectory Chart for Multiple Jets Discharging into a Stratified, Stagnant Large Body of Water: MNS L/D = 1.5, $Z_s/D = 0$, $\theta = 0°$

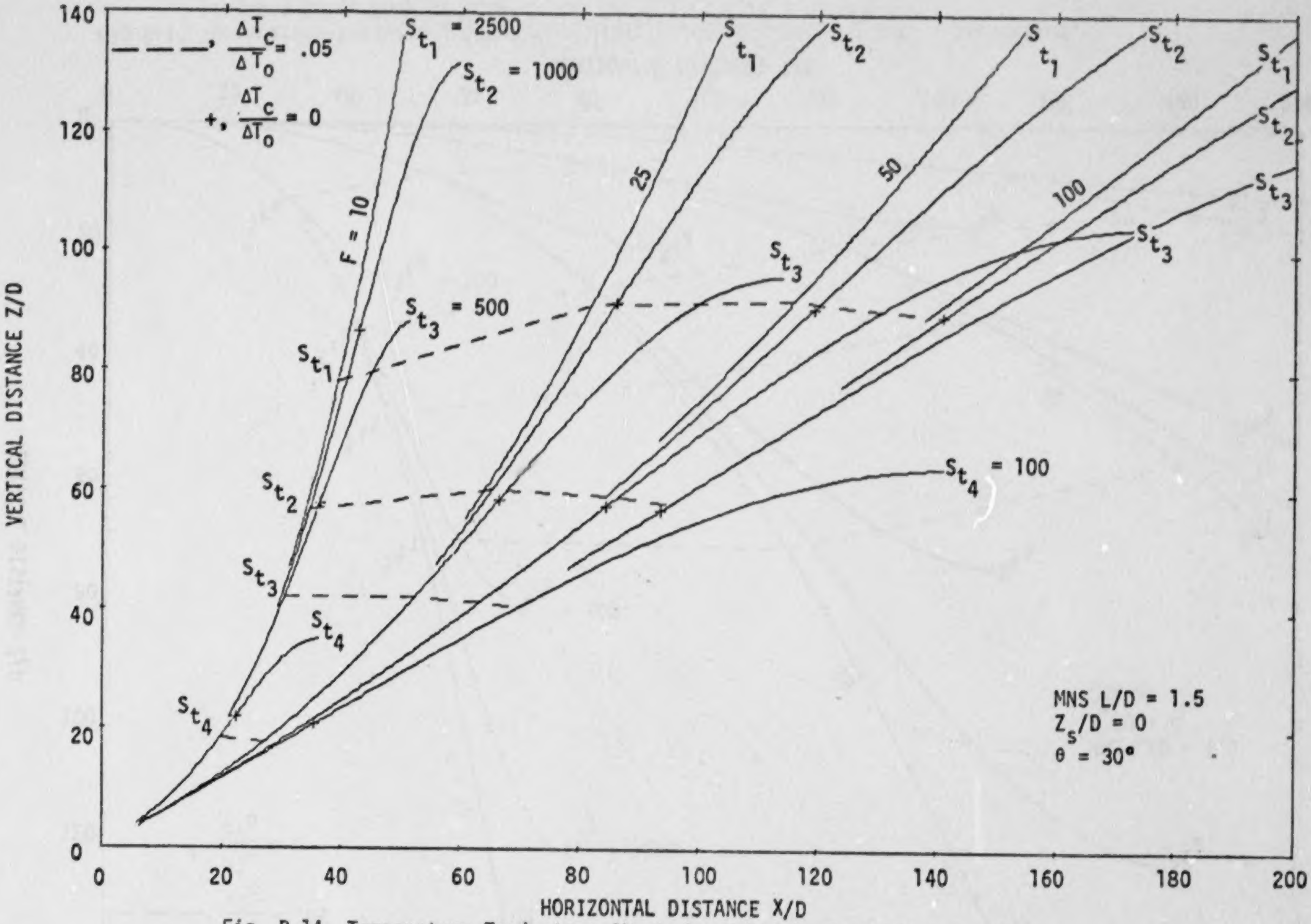

Fig. B-14 Temperature-Trajectory Chart for Multiple Jets Discharging into a Stratified, Stagnant Large Body of Water: MNS L/D = 1.5, $Z_s/D = 0$, θ = 30°

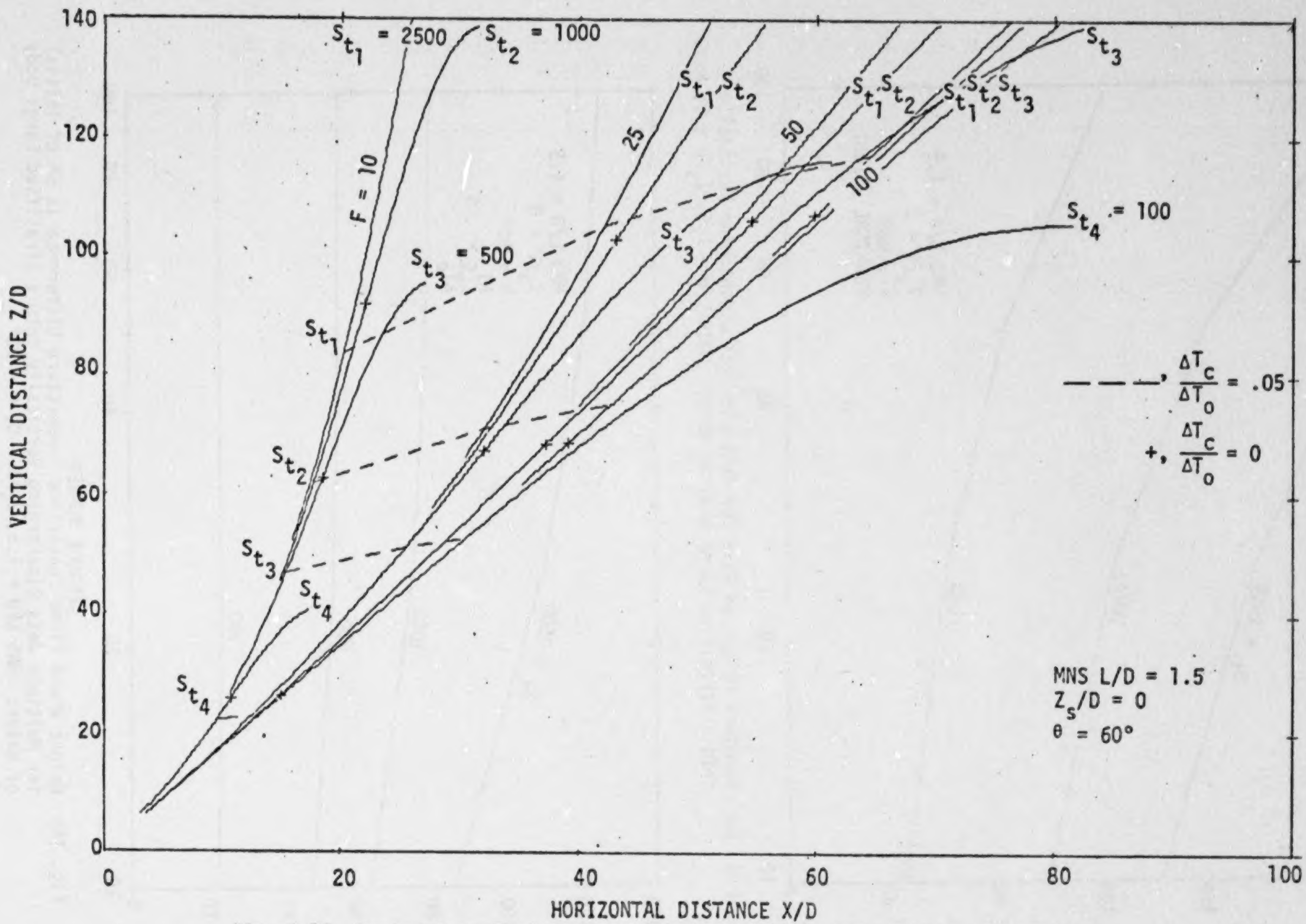

Fig. B-15 Temperature-Trajectory Chart for Multiple Jets Discharging into a Stratified, Stagnant Large Body of Water: MNS L/D = 1.5, $Z_s/D = 0$, $\Theta = 60°$

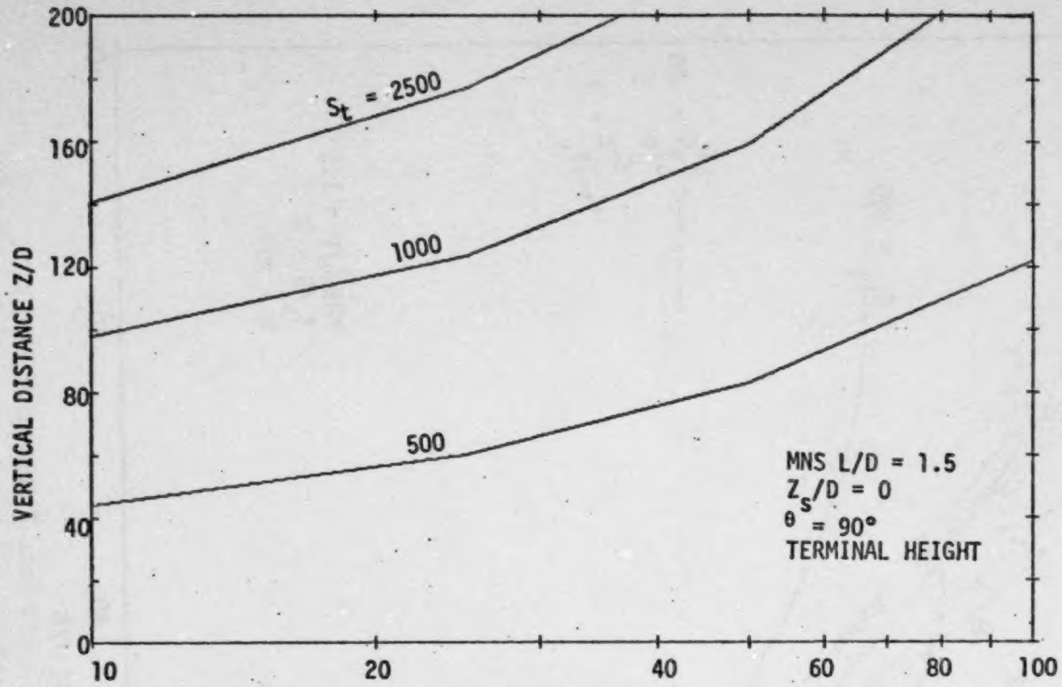

Fig. 16a Terminal Height of Rise for Multiple Jets Discharging Vertically into a Stratified Large Body of Water: MNS L/D = 1.5, $Z_s/D = 0$, $\Theta = 90°$

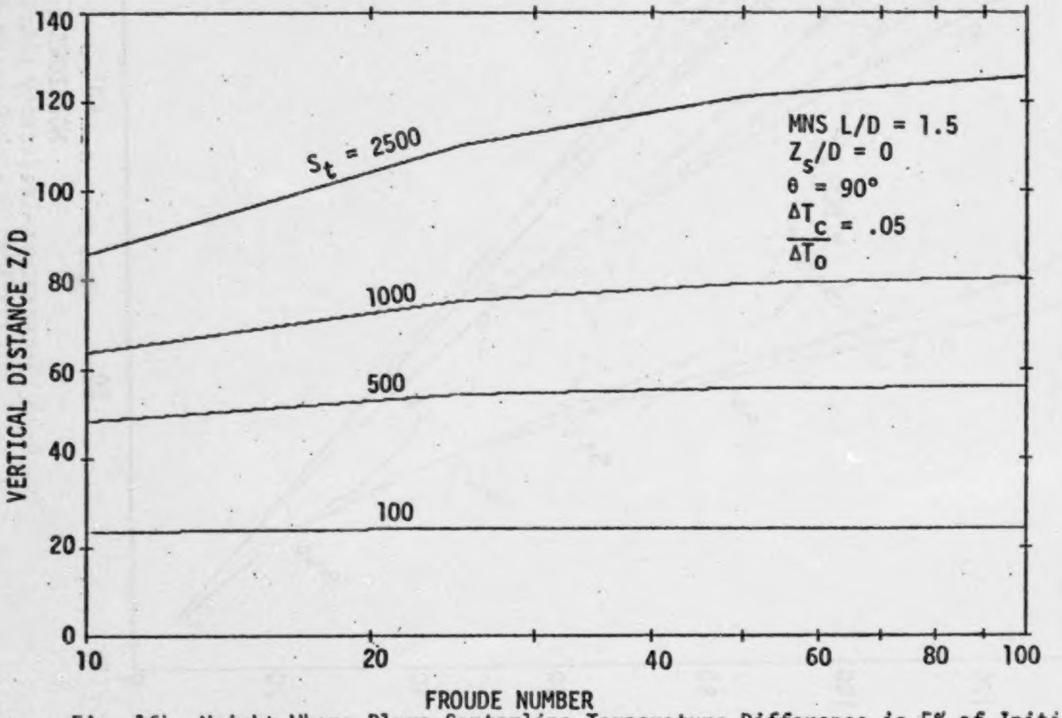

Fig. 16b Height Where Plume Centerline Temperature Difference is 5% of Initial for Multiple Jets Discharging Vertically into a Stratified Large Body of Water: MNS L/D = 1.5, $Z_s/D = 0$, $\Theta = 90°$

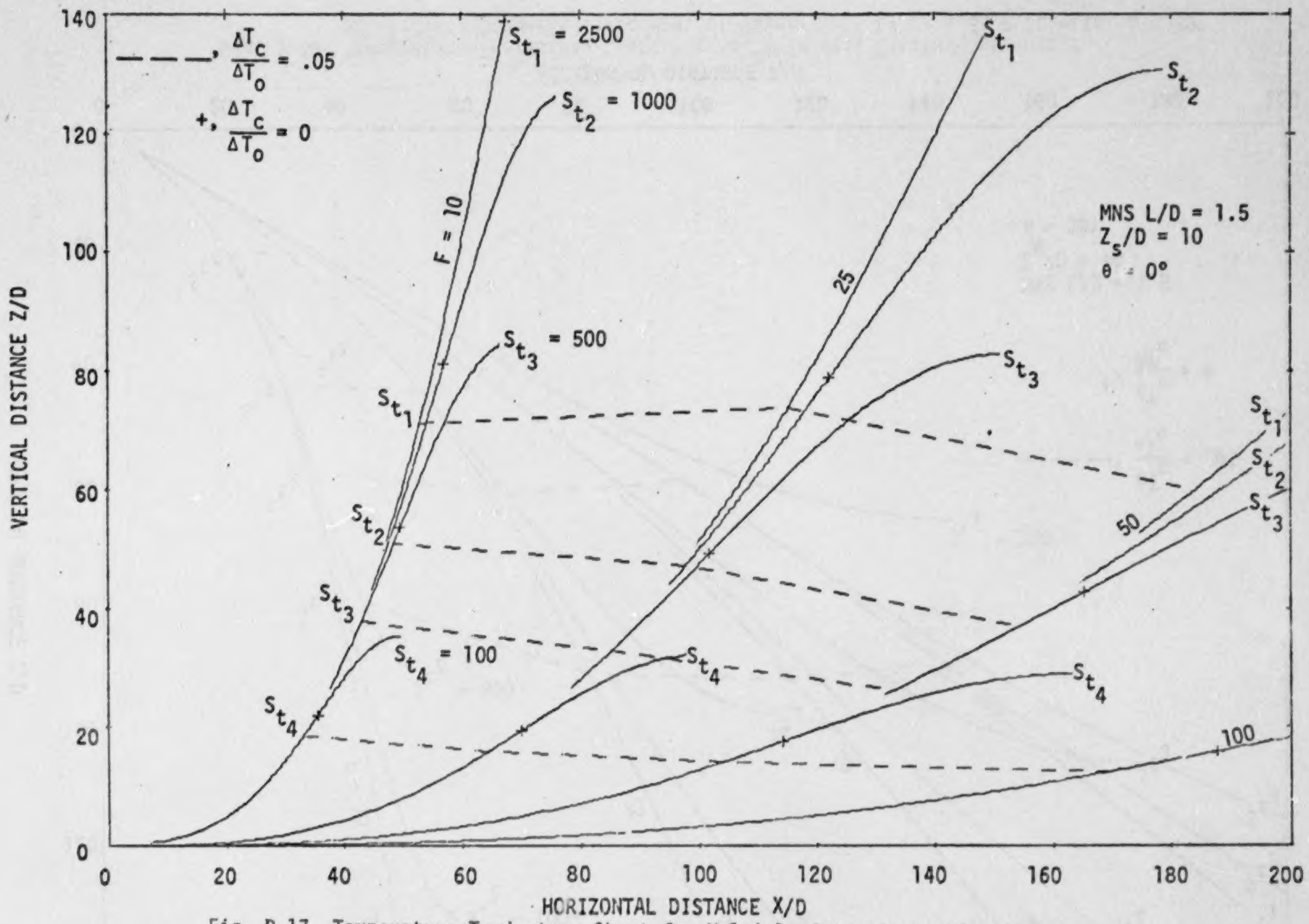

Fig. B-17 Temperature-Trajectory Chart for Multiple Jets Discharging into a Stratified, Stagnant Large Body of Water: MNS L/D = 1.5, $Z_s/D = 10$, $\Theta = 0°$

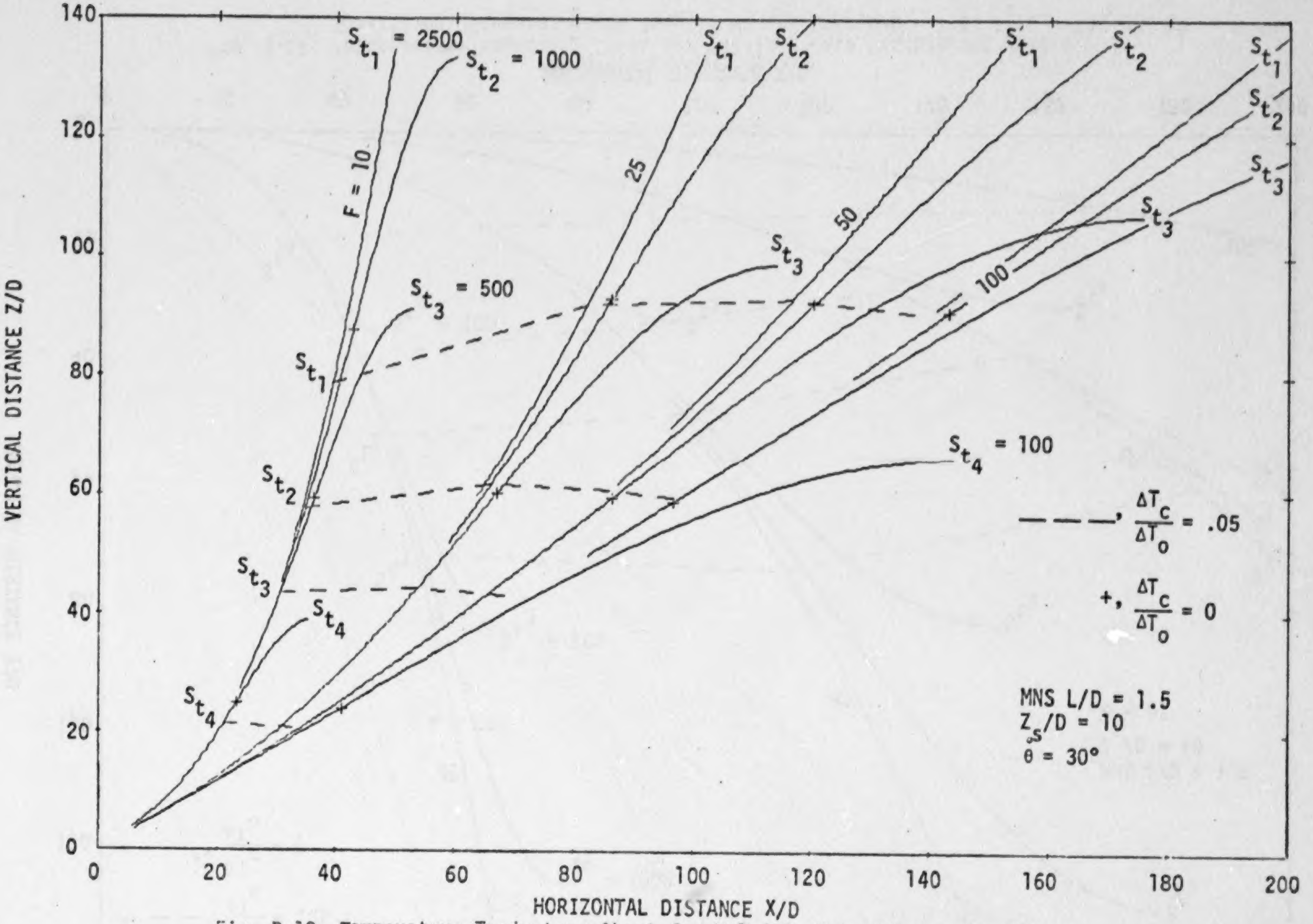

Fig. B-18 Temperature-Trajectory Chart for Multiple Jets Discharging into a Stratified, Stagnant Large Body of Water: MNS L/D = 1.5, $Z_s/D = 10$, Θ = 30°

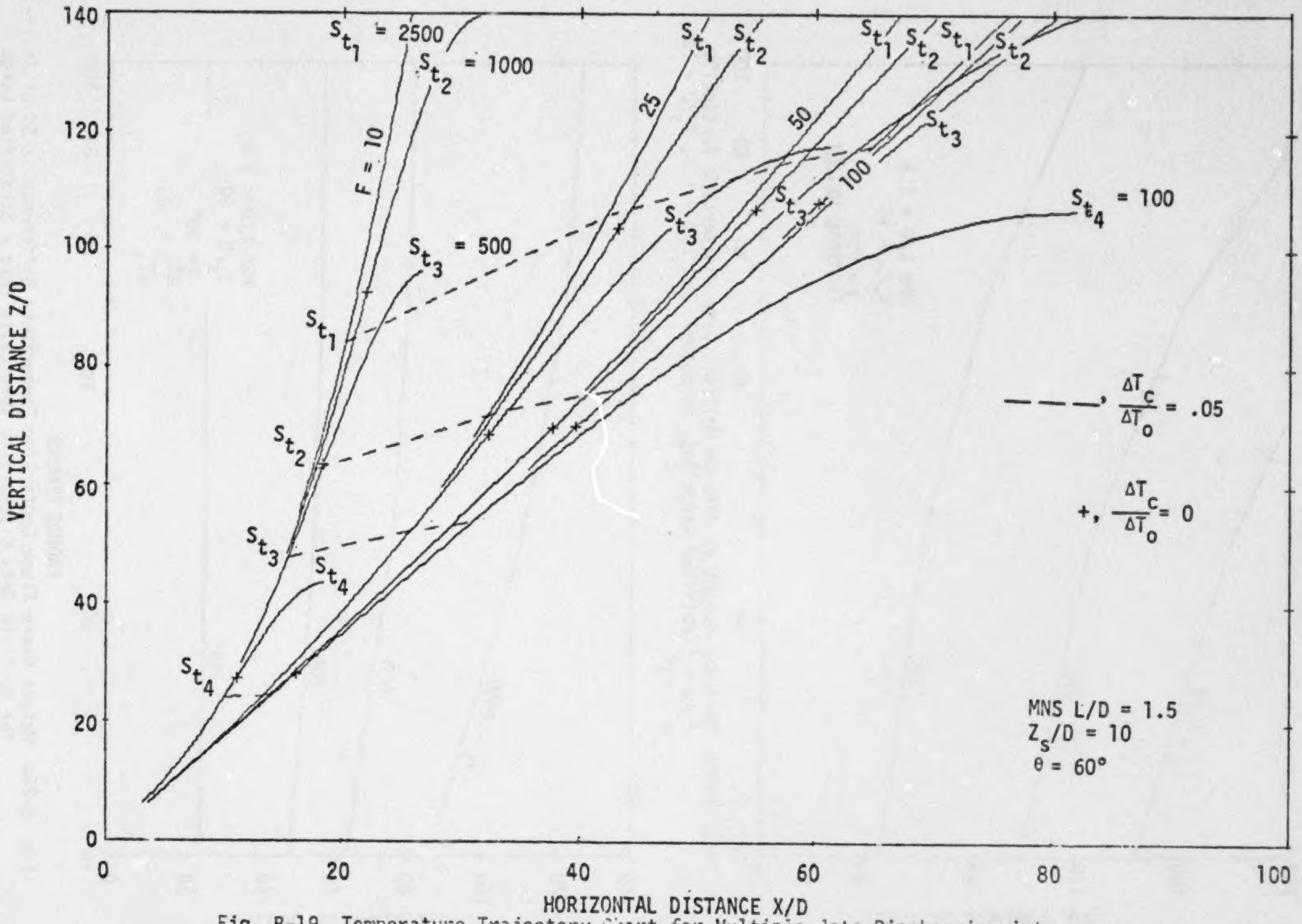

Fig. B-19 Temperature-Trajectory Chart for Multiple Jets Discharging into a Stratified, Stagnant Large Body of Water: MNS L/D = 1.5, Z_s/D = 10, θ = 60°

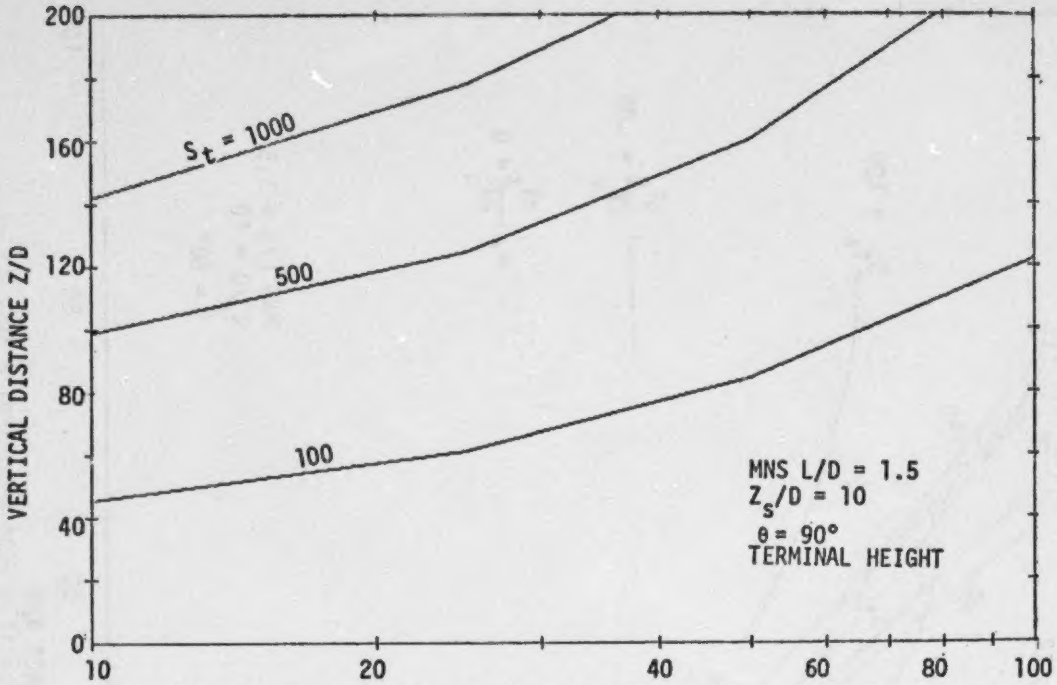

Fig. B-20a Terminal Height of Rise for Multiple Jets Discharging Vertically into a Stratified Large Body of Water: MNS L/D = 1.5, $Z_s/D = 10$ Θ = 90°

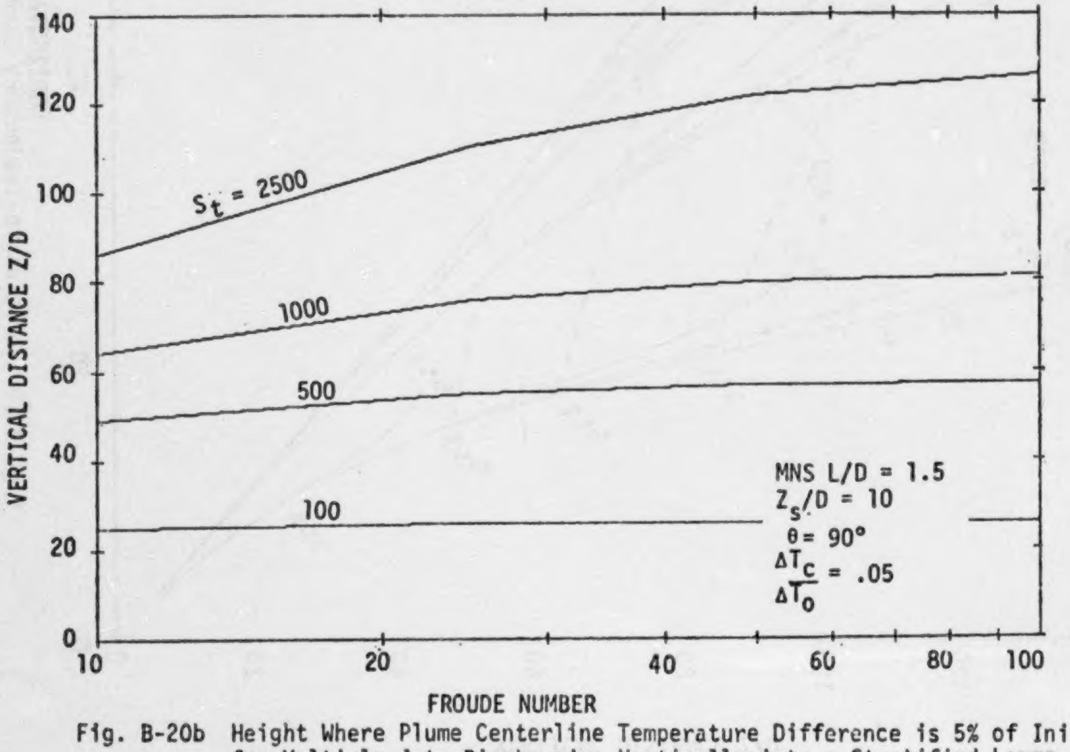

Fig. B-20b Height Where Plume Centerline Temperature Difference is 5% of Initial for Multiple Jets Discharging Vertically into a Stratified Large Body of Water: MNS L/D = 1.5, $Z_s/D = 10$, Θ = 90°

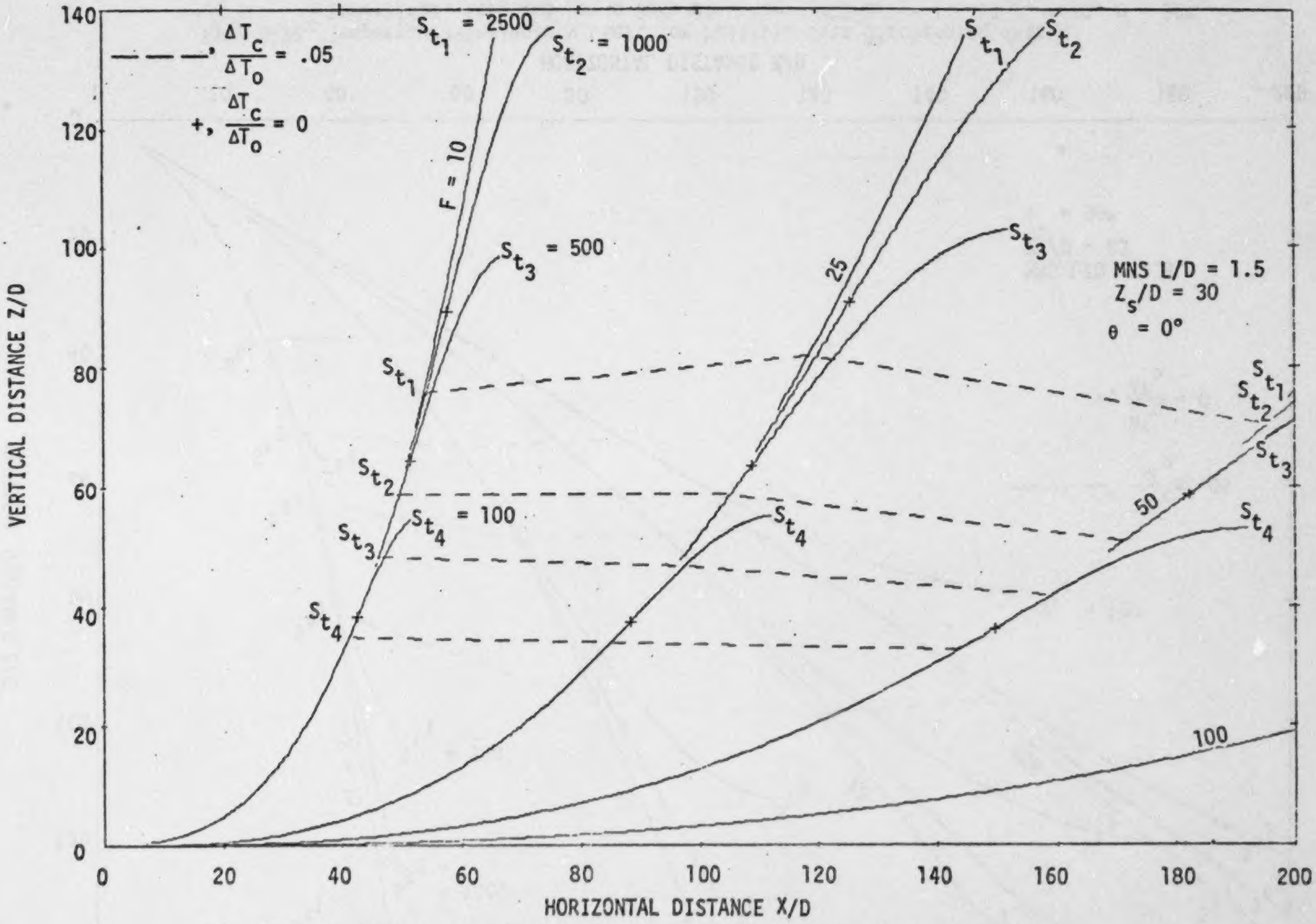

Fig. B-21 Temperature-Trajectory Chart for Multiple Jets Discharging into a Stratified, Stagnant Large Body of Water: MNS L/D = 20, $Z_s/D = 0$, $\Theta = 0°$

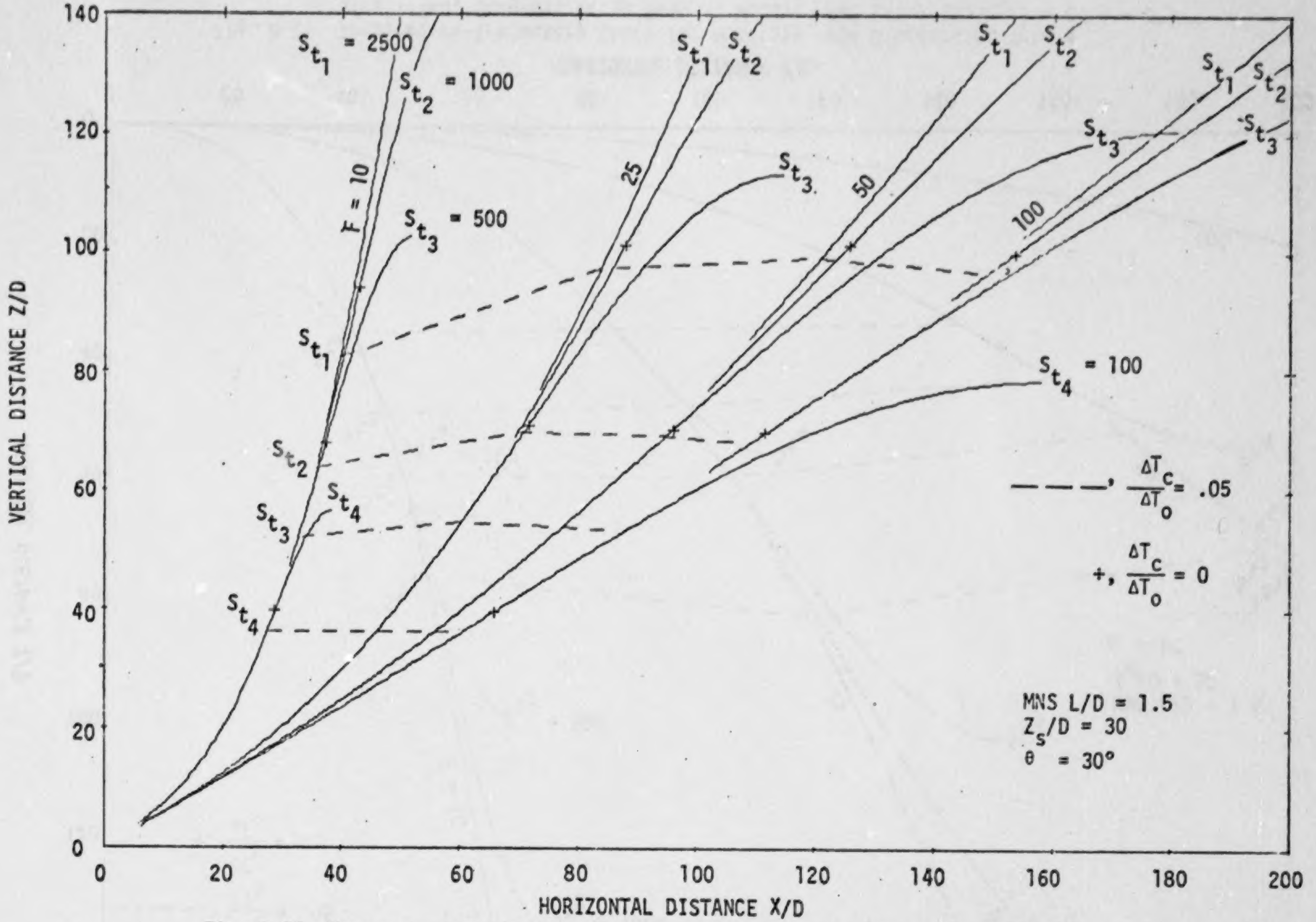

Fig. B-22 Temperature-Trajectory Chart for Multiple Jets Discharging into a Stratified, Stagnant Large Body of Water: MNS L/D = 1.5, $Z_s/D = 30$, Θ = 30°

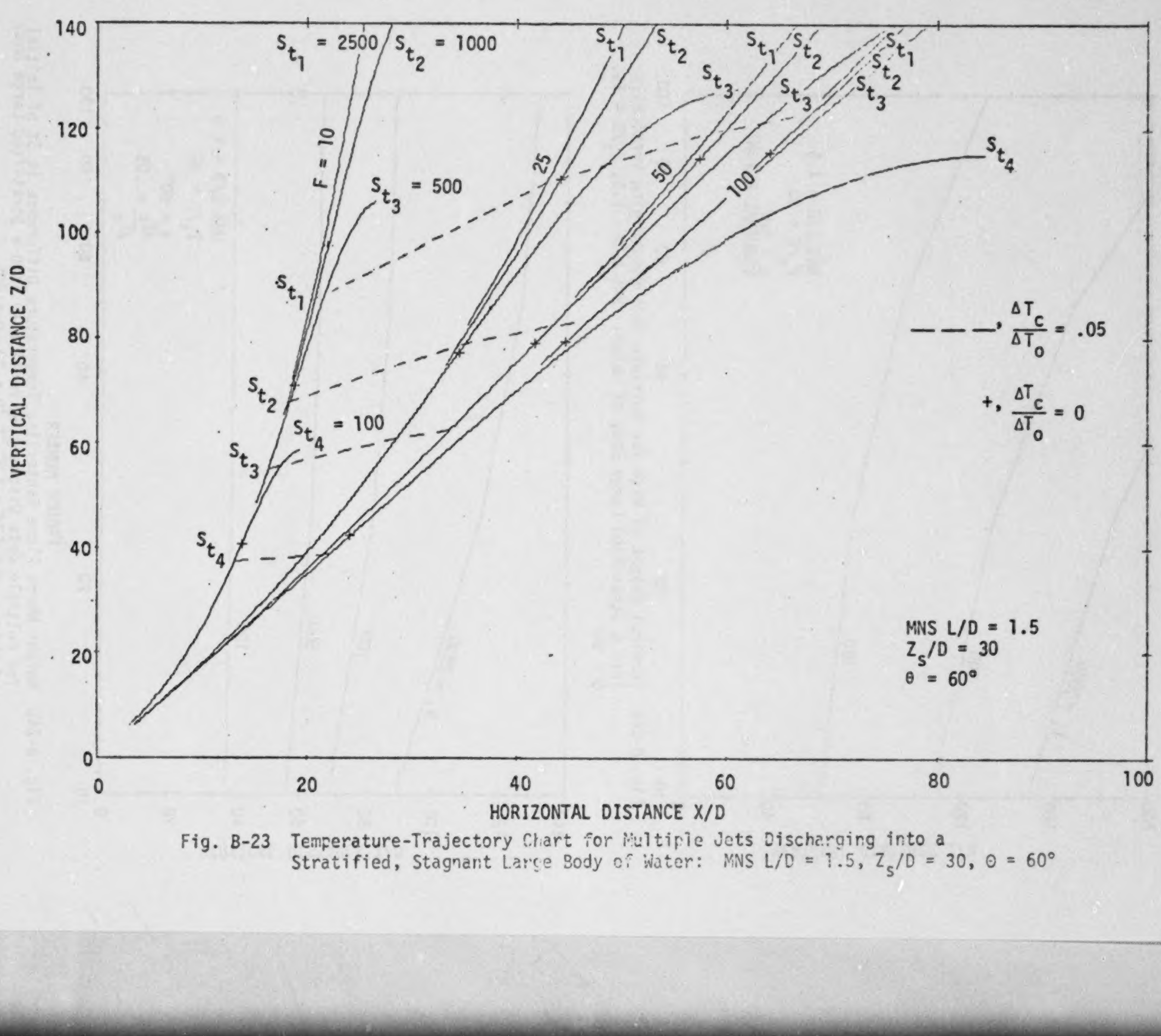

Fig. B-23 Temperature-Trajectory Chart for Multiple Jets Discharging into a Stratified, Stagnant Large Body of Water: MNS L/D = 1.5, Z_s/D = 30, Θ = 60°

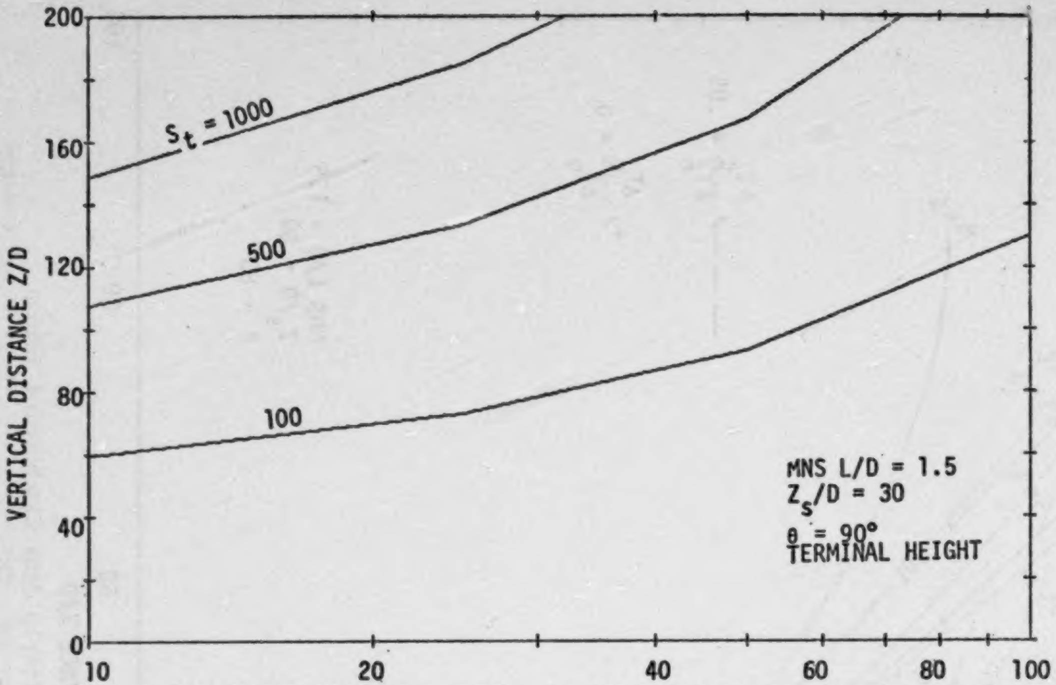

Fig. B-24a Terminal Height of Rise for Multiple Jets Discharging Vertically into a Stratified Large Body of Water: MNS L/D = 1.5, $Z_s/D = 30$, Θ = 90°

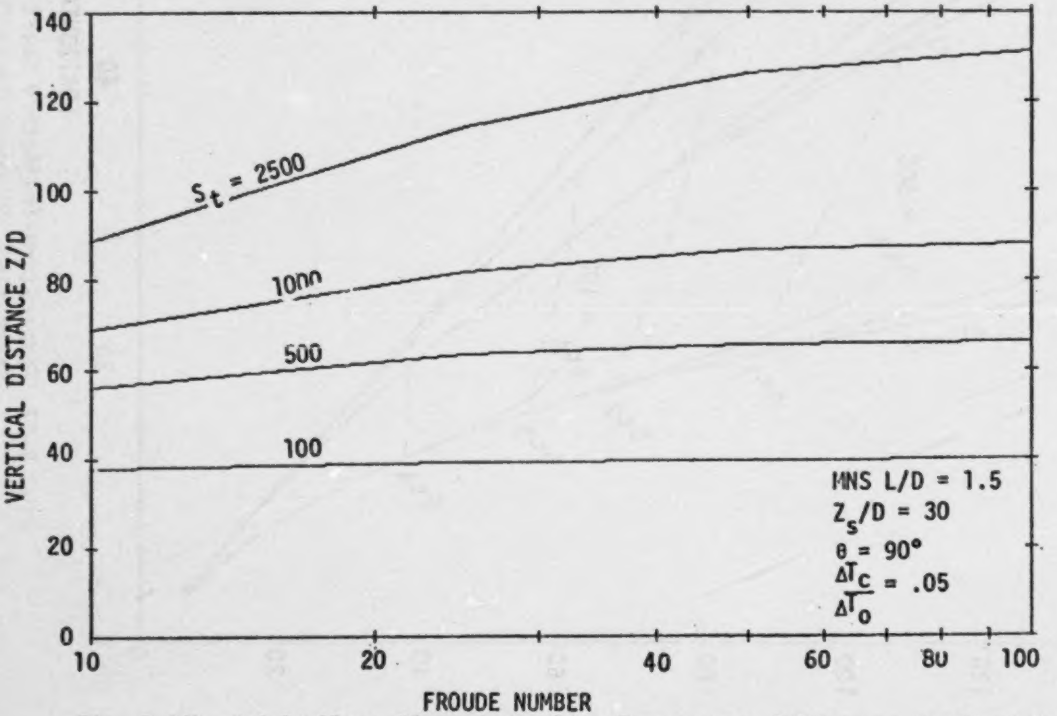

Fig. B-24b Height Where Plume Centerline Temperature Difference is 5% of Initial for Multiple Jets Discharging Vertically into a Stratified Large Body of Water: MNS L/D = 1.5, $Z_s/D = 30$, Θ = 90°

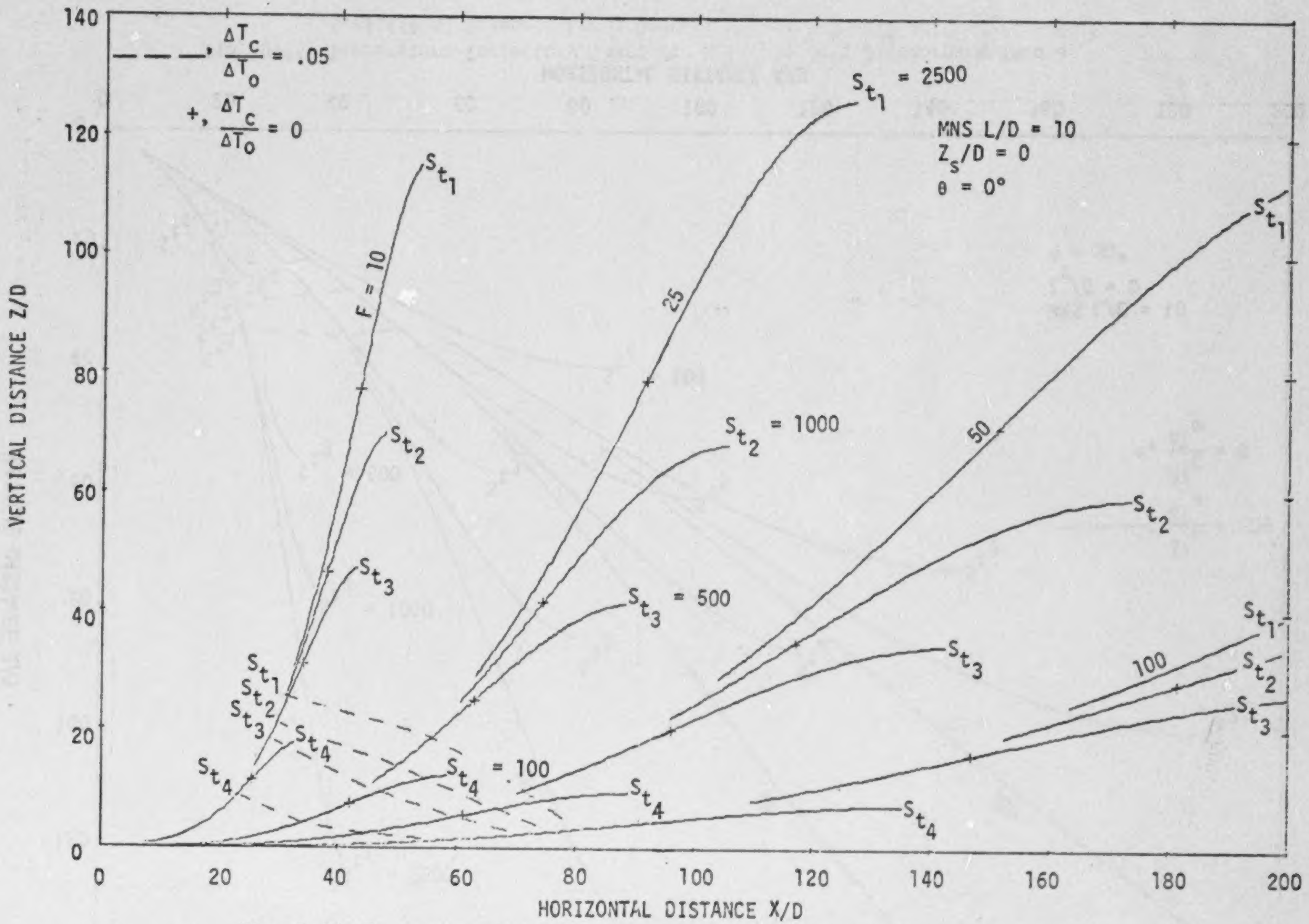

Fig. B-25 Temperature-Trajectory Chart for Multiple Jets Discharging into a Stratified, Stagnant Large Body of Water: MNS L/D = 10, $Z_s/D = 0$, $\Theta = 0°$

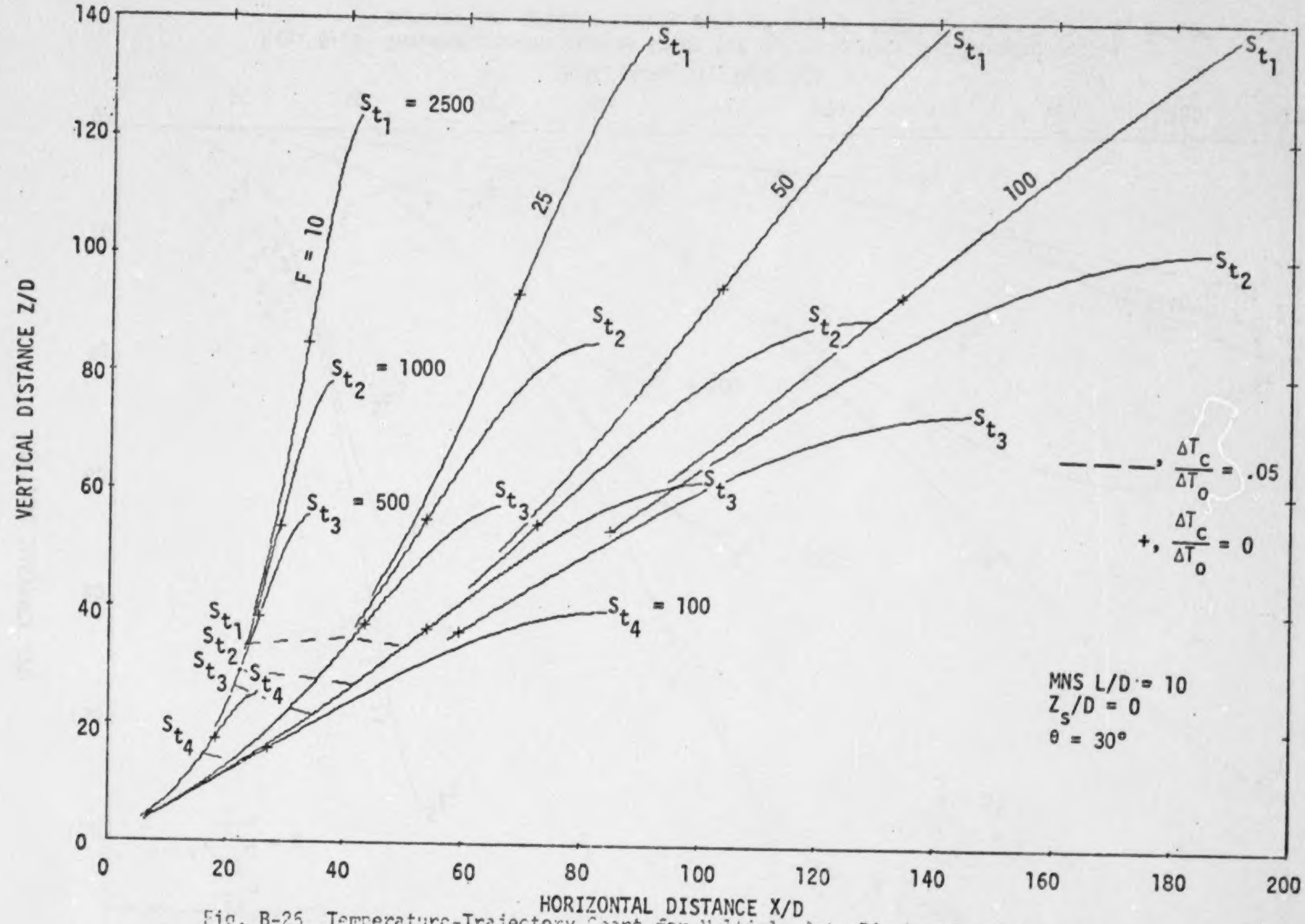

Fig. B-25 Temperature-Trajectory Chart for Multiple Jets Discharging into a Stratified, Stagnant Large Body of Water: MNS L/D = 10, Z_s/D = 0, θ = 30°

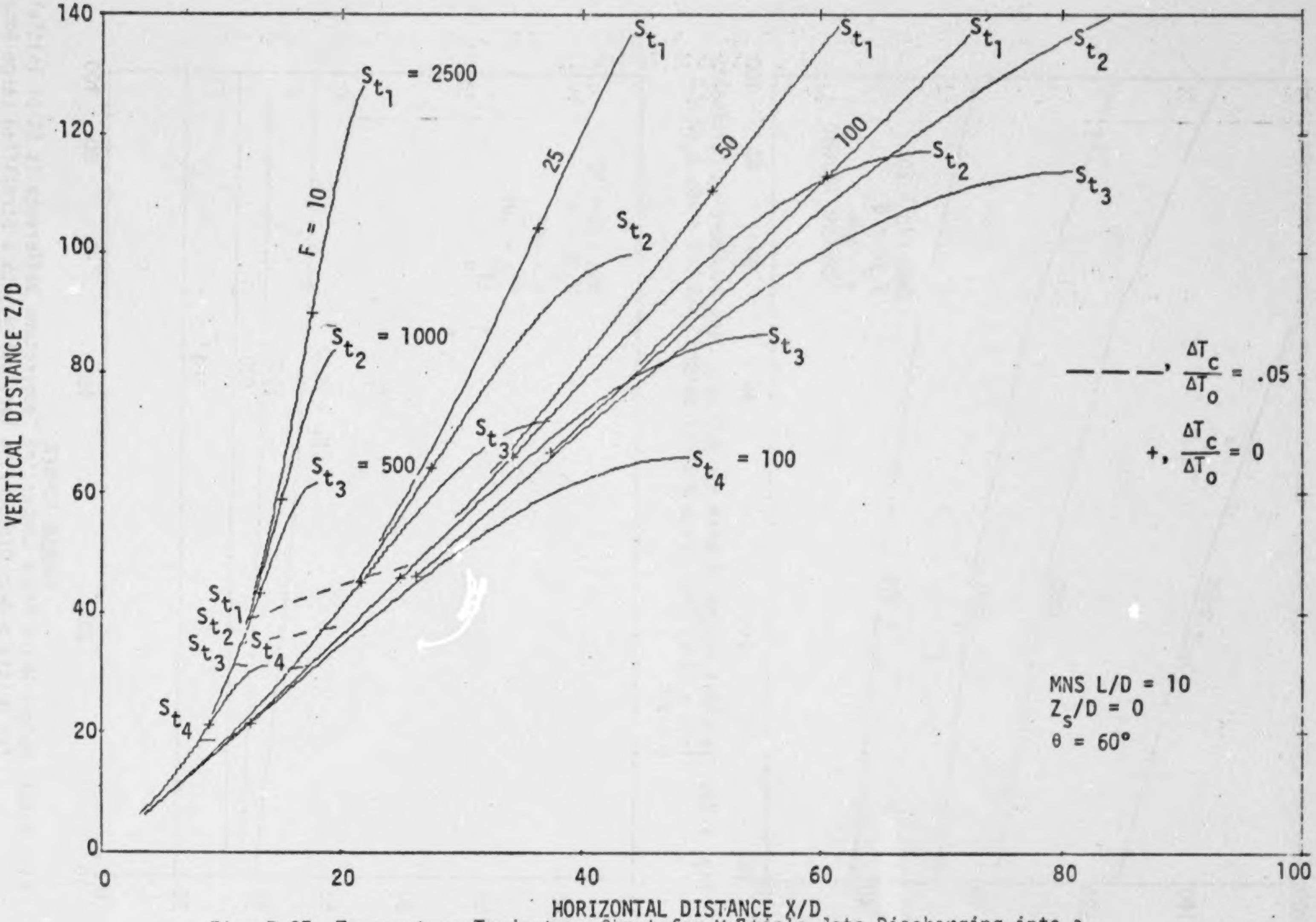

Fig. B-27 Temperature-Trajectory Chart for Multiple Jets Discharging into a Stratified, Stagnant Large Body of Water: MNS L/D = 10, Z_s/D = 0, Θ = 60°

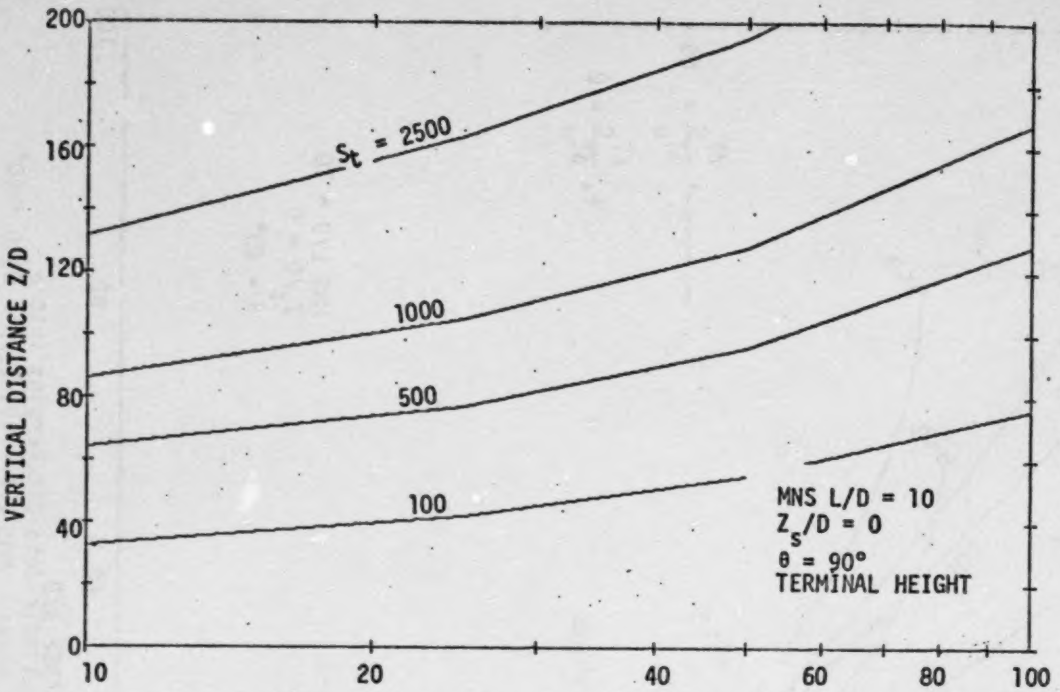

Fig. B-28a Terminal Height of Rise for Multiple Jets Discharging Vertically into a Stratified Large Body of Water: MNS L/D = 10, $Z_s/D = 0$ θ = 90°

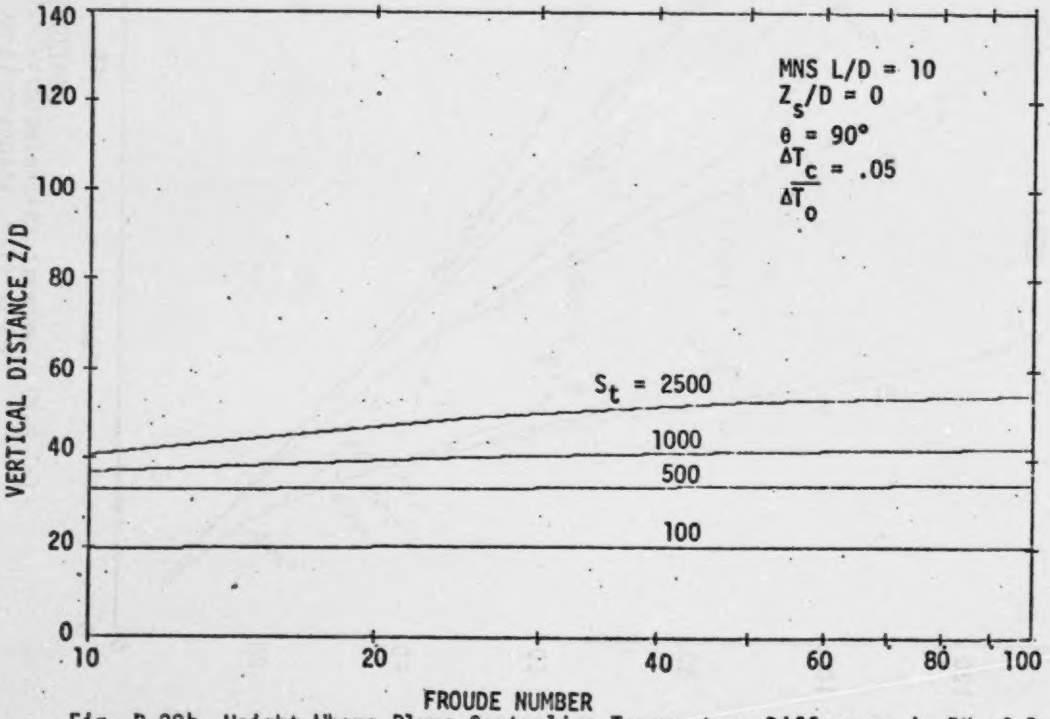

Fig. B-28b Height Where Plume Centerline Temperature Difference is 5% of Initial for Multiple Jets Discharging Vertically into a Stratified Large Body of Water: MNS L/D = 10, $Z_s/D = 0$, θ = 90°

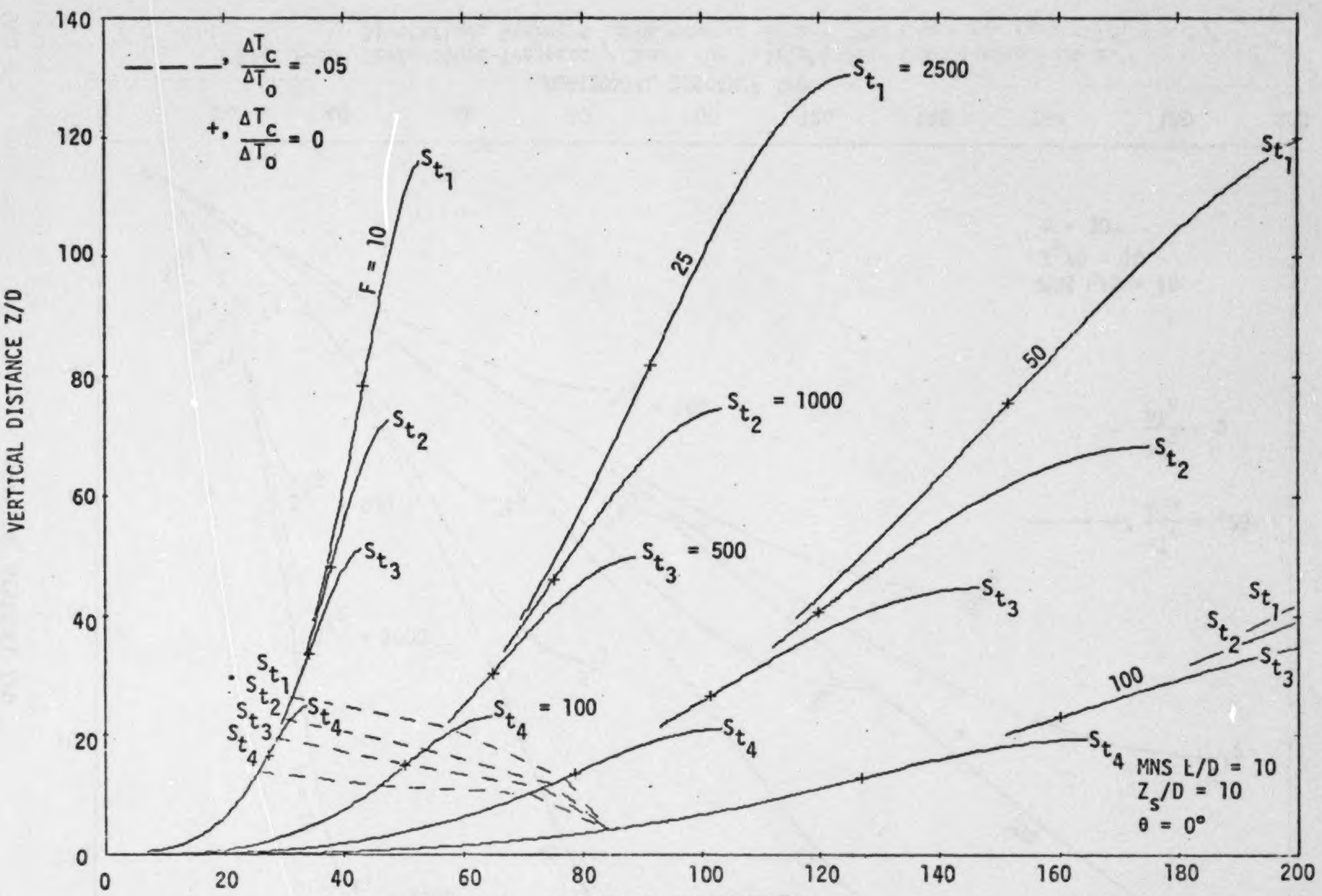

Fig. B-29 Temperature-Trajectory Chart for Multiple Jets Discharging into a Stratified, Stagnant Large Body of Water: MNS L/D = 10, $Z_s/D = 10$, Θ = 0°

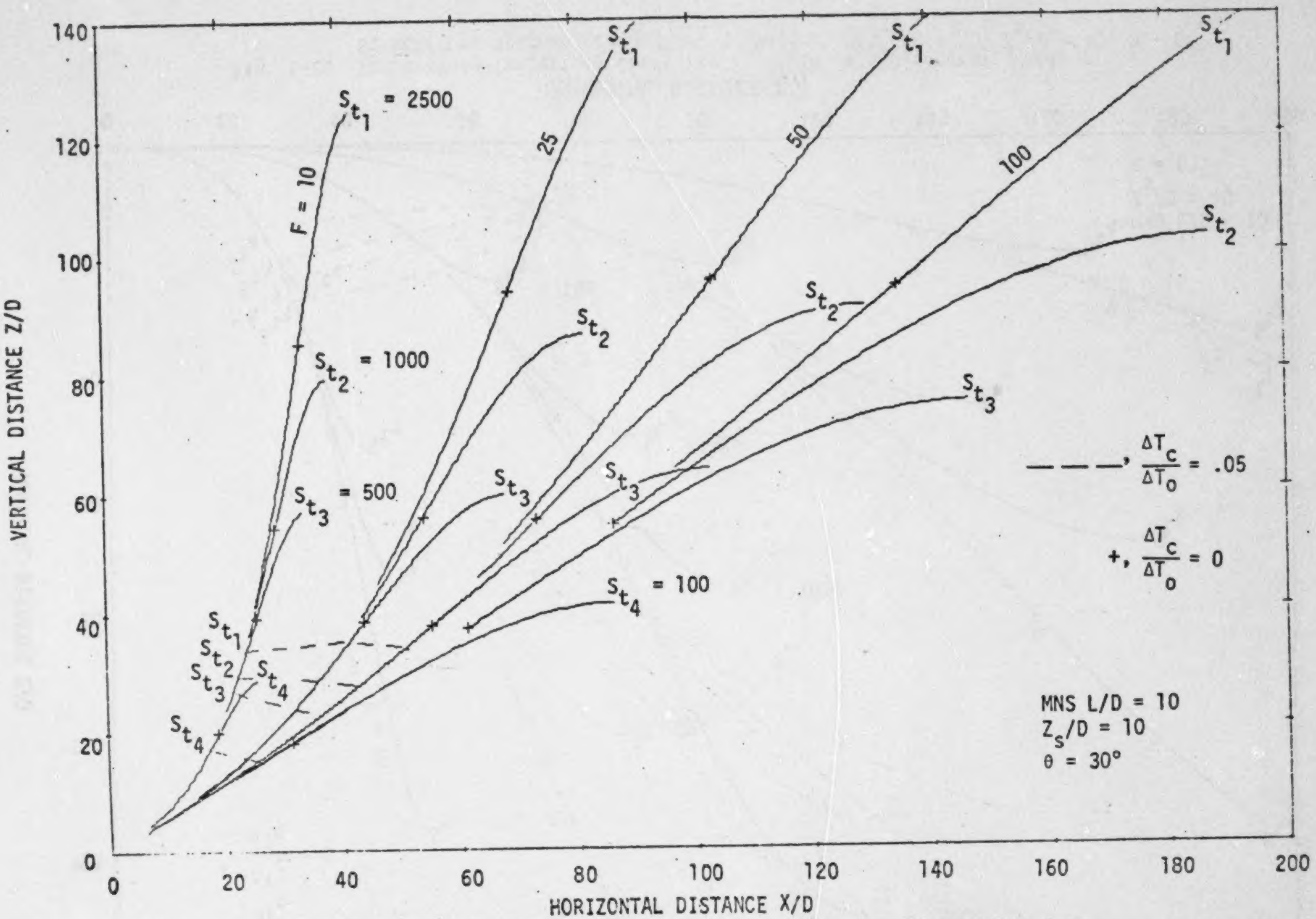

Fig. B-30 Temperature-Trajectory Chart for Multiple Jets Discharging into a Stratified, Stagnant Large Body of Water: MNS L/D = 10, $Z_s/D = 10$, $\Theta = 30°$

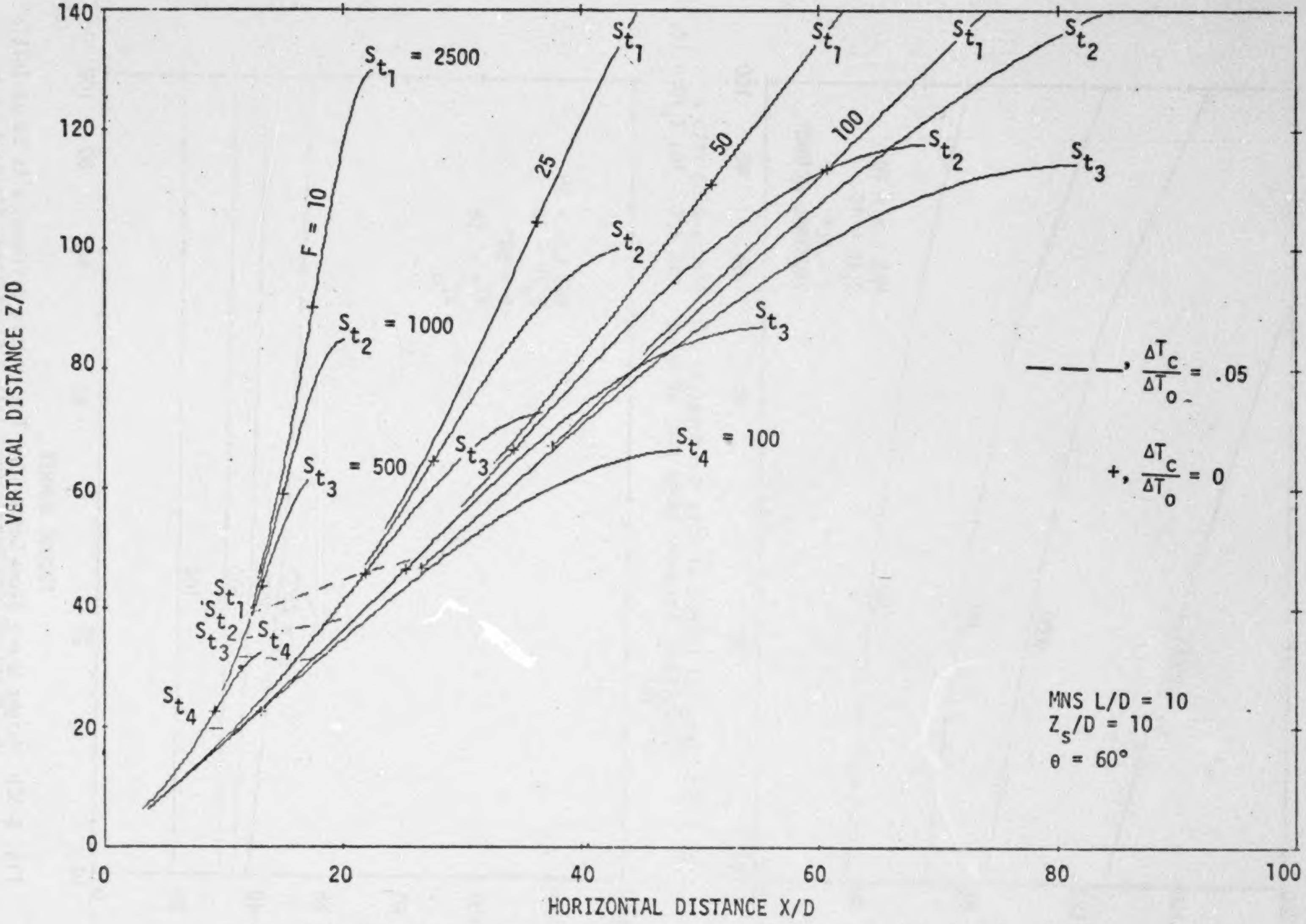

Fig. B-31 Temperature-Trajectory Chart for Multiple Jets Discharging into a Stratified, Stagnant Large Body of Water: MNS L/D = 10, Z_s/D = 10, Θ = 60°

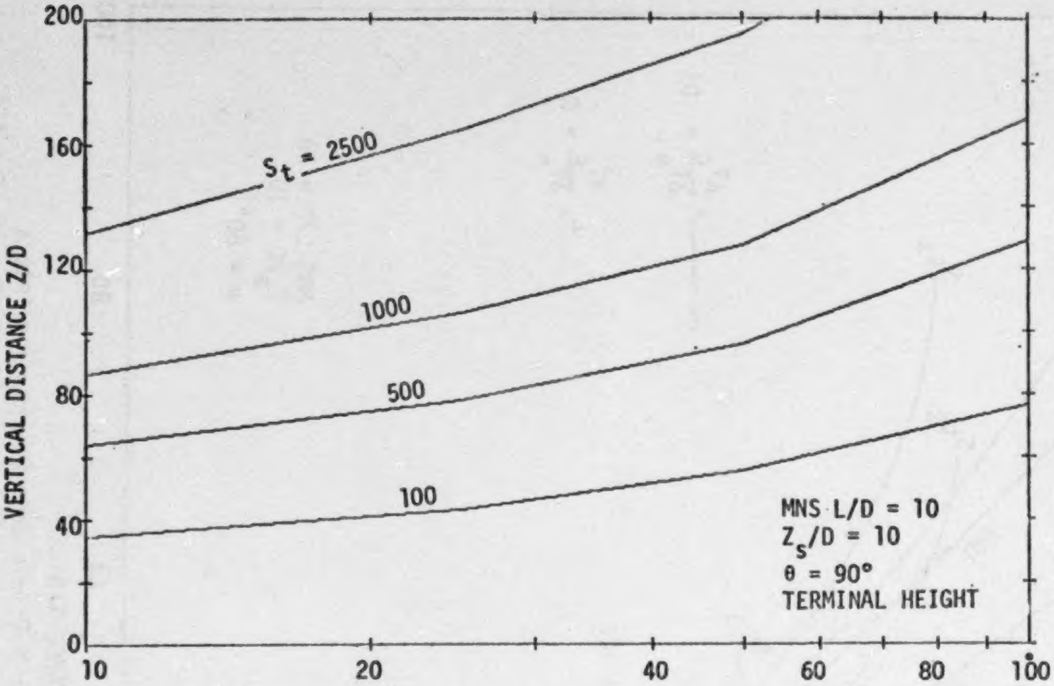

Fig. B-32a Terminal Height of Rise for Multiple Jets Discharging into a Stratified, Stagnant Large Body of Water: MNS L/D = 10, Z_s/D = 10, Θ = 90°

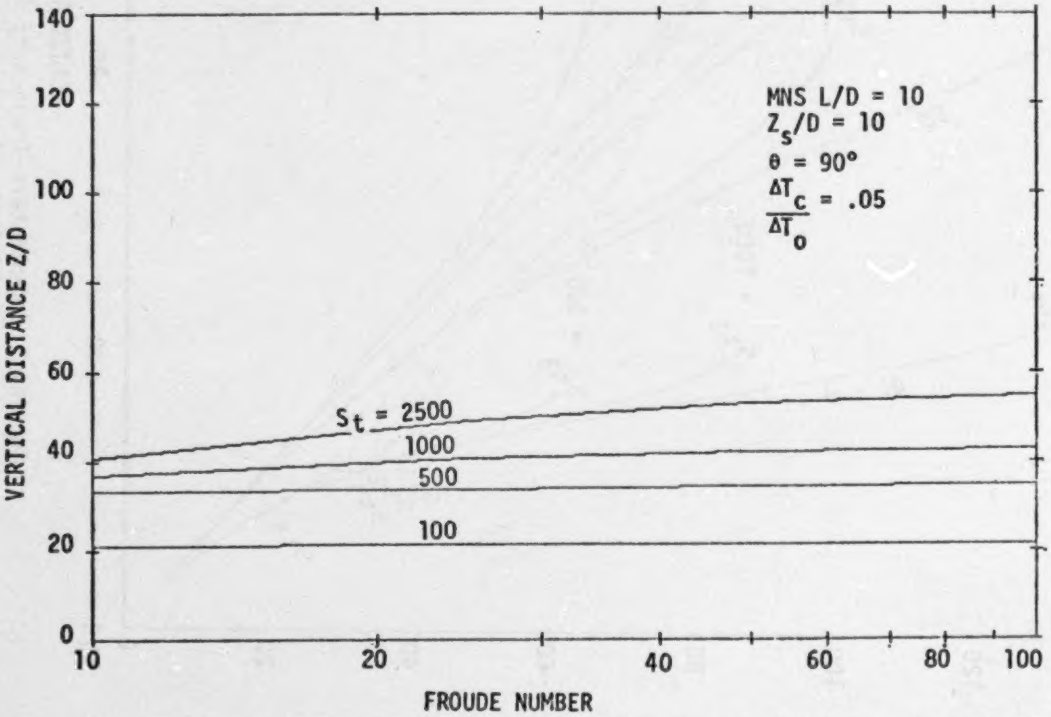

Fig. B-32b Height Where Plume Centerline Temperature Difference is 5% of Initia' for Multiple Jets Discharging into a Stratified, Stagnant Large Body of Water: MNS L/D = 10, Z_s/D = 10, Θ = 90°

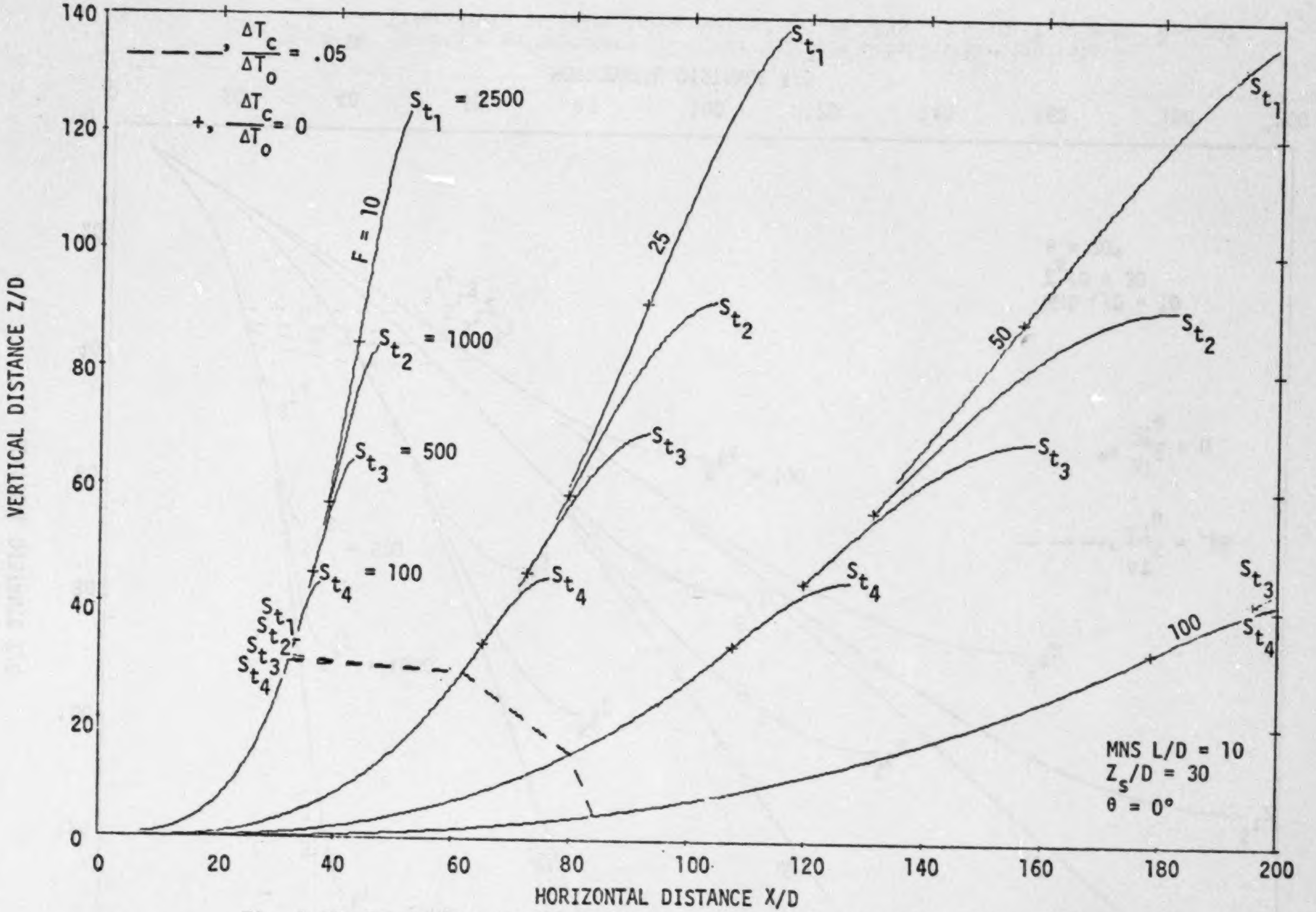

Fig. B-33 Temperature-Trajectory Chart for Multiple Jets Discharging into a Stratified, Stagnant Large Body of Water: MNS L/D = 10, $Z_s/D = 30$, θ = 0°

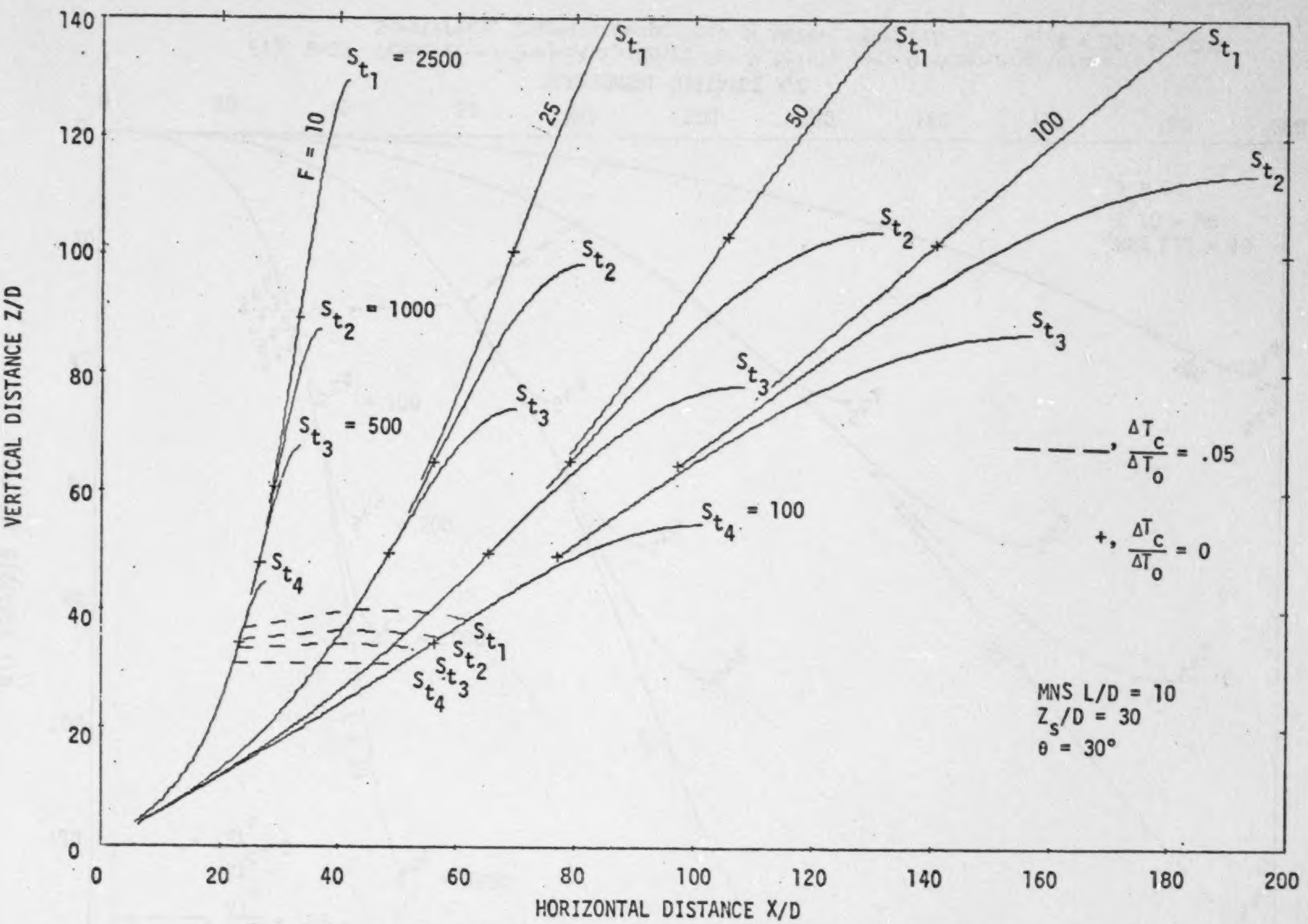

Fig. B-34 Temperature-Trajectory Chart for Multiple Jets Discharging into a Stratified, Stagnant Large Body of Water: MNS L/D = 10, Z_s/D = 30, θ = 30°

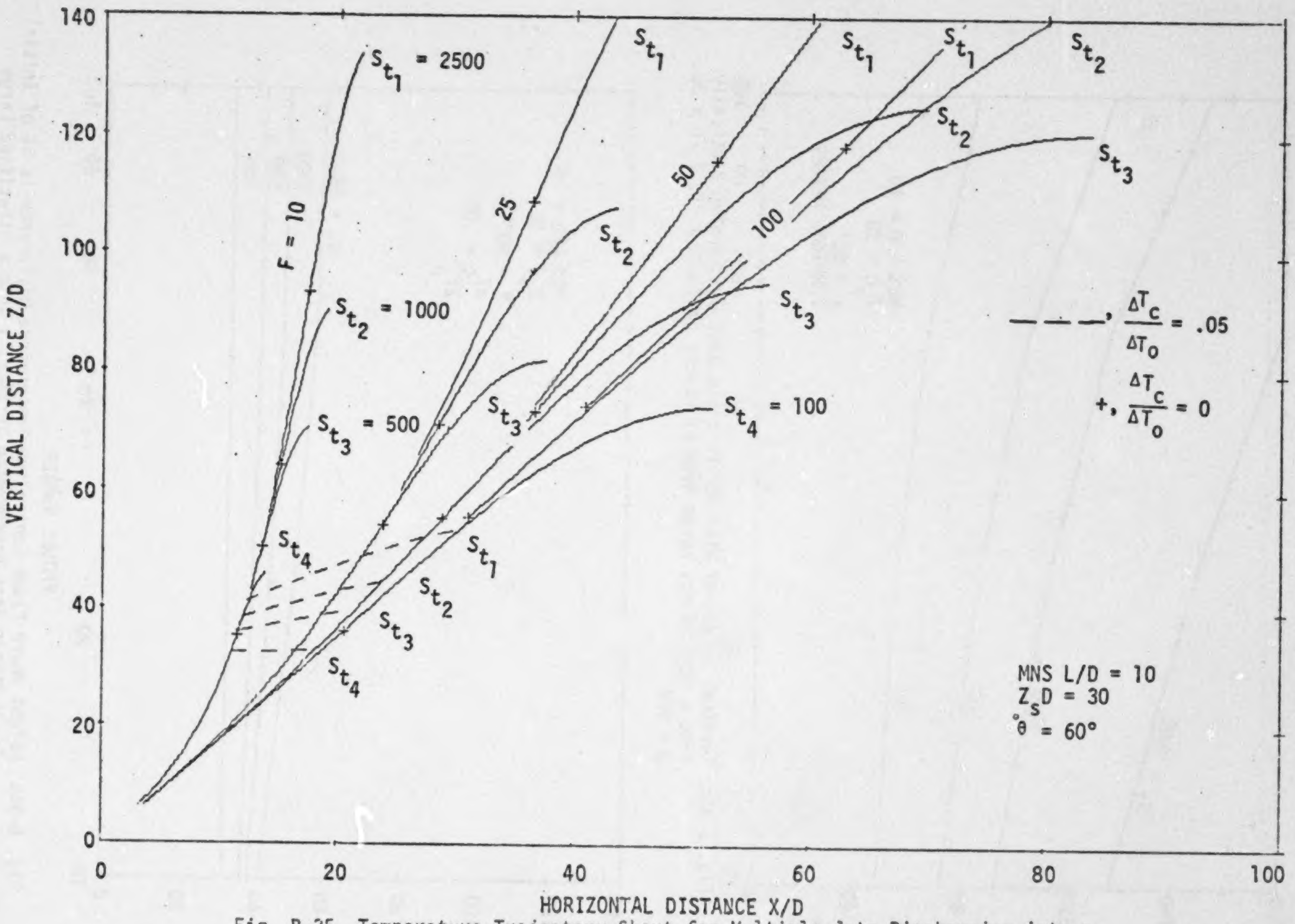

Fig. B-35 Temperature-Trajectory Chart for Multiple Jets Discharging into a Stratified, Stagnant Large Body of Water: MNS L/D = 10, Z_sD = 30, Θ = 60°

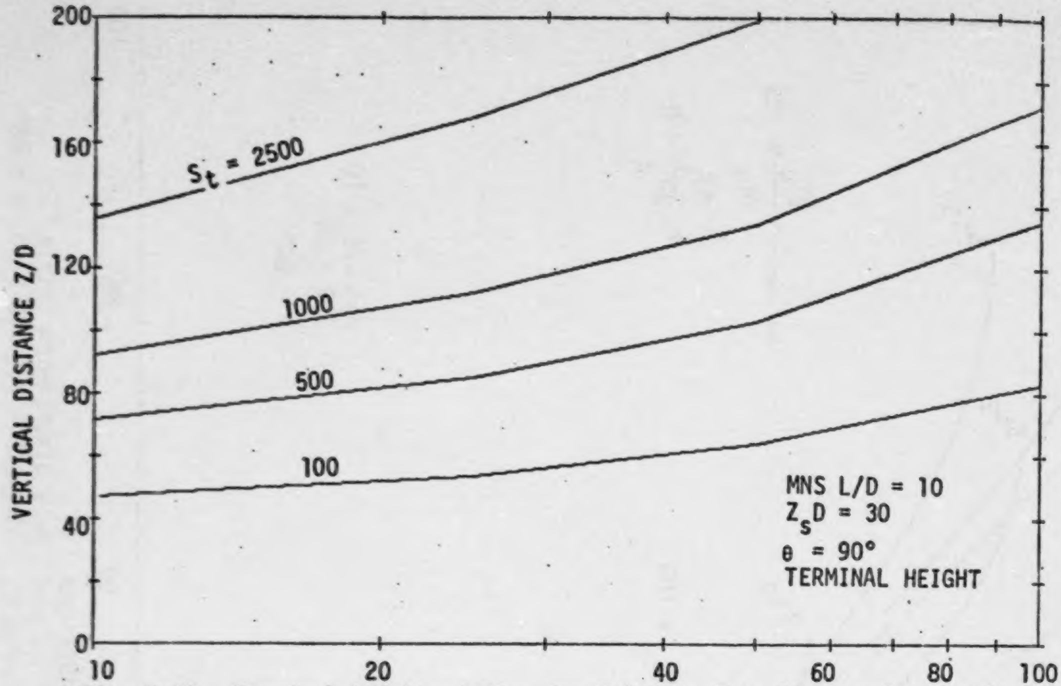

Fig. B-36a Terminal Height of Rise for Multiple Jets Discharging Vertically into a Stratified, Large Body of Water: MNS L/D = 10, Z_s/D = 30, θ = 90°

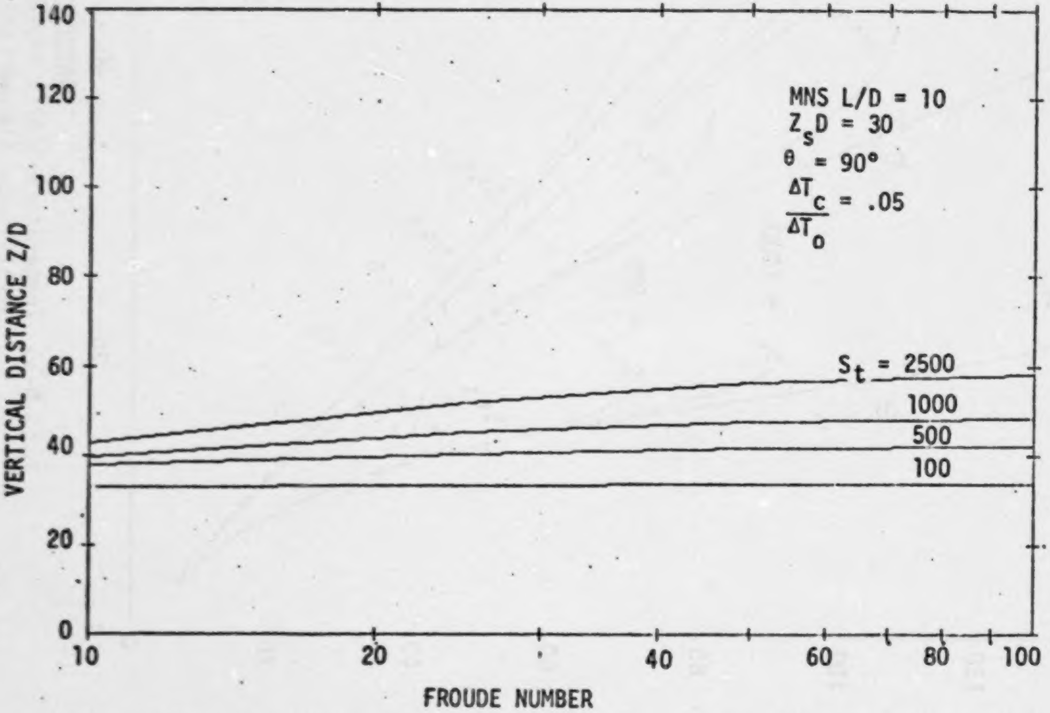

Fig. B-36b Height Where Plume Centerline Temperature Difference is 5% of Initial for Multiple Jets Discharging Vertically into a Stratified Large Body of Water: MNS L/D = 10, Z_sD = 30, θ = 90°

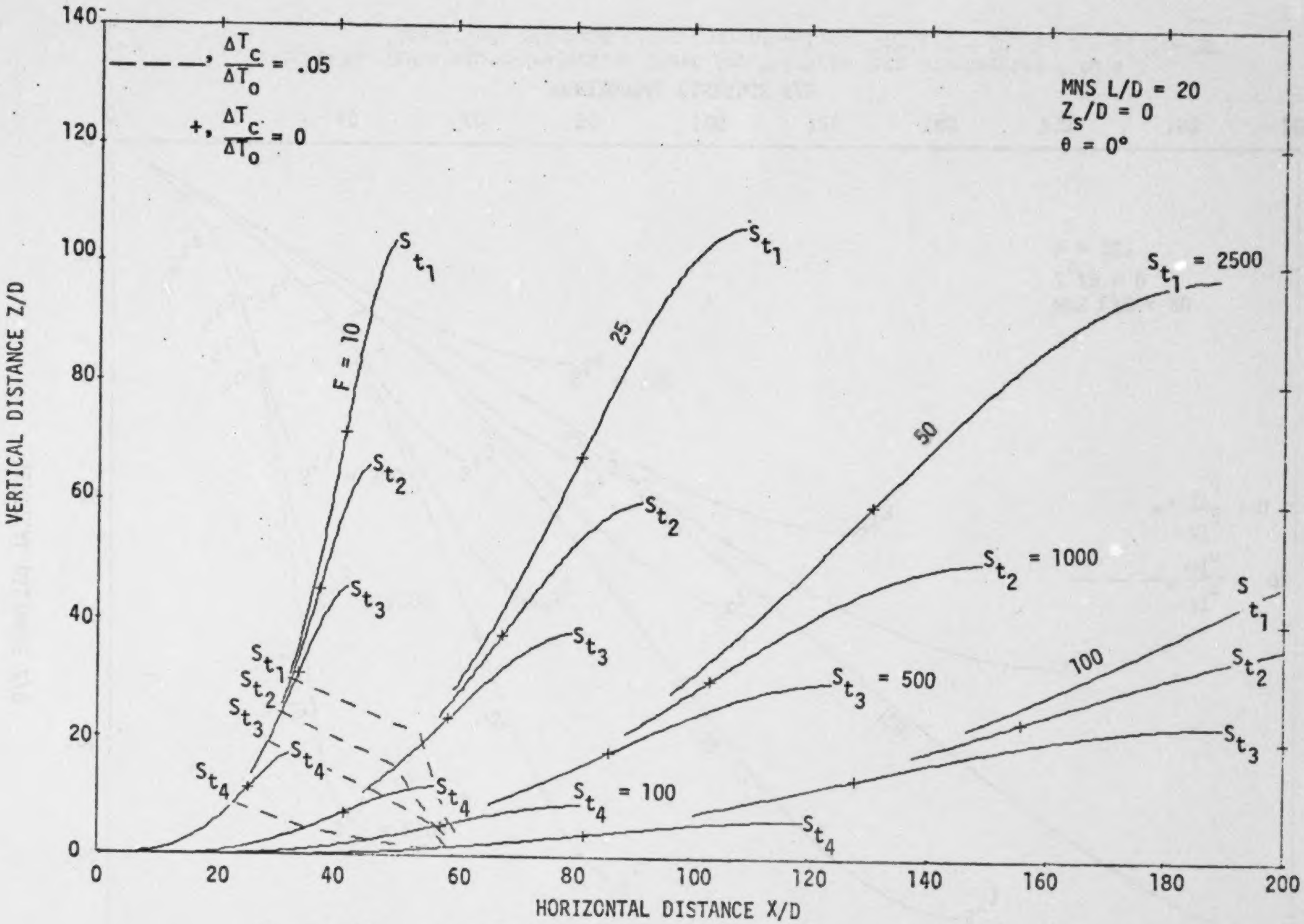

Fig. B-37 Temperature-Trajectory Chart for Multiple Jets Discharging into a Stratified, Stagnant Large Body of Water: MNS L/D = 20, $Z_s/D = 0$, $\theta = 0°$

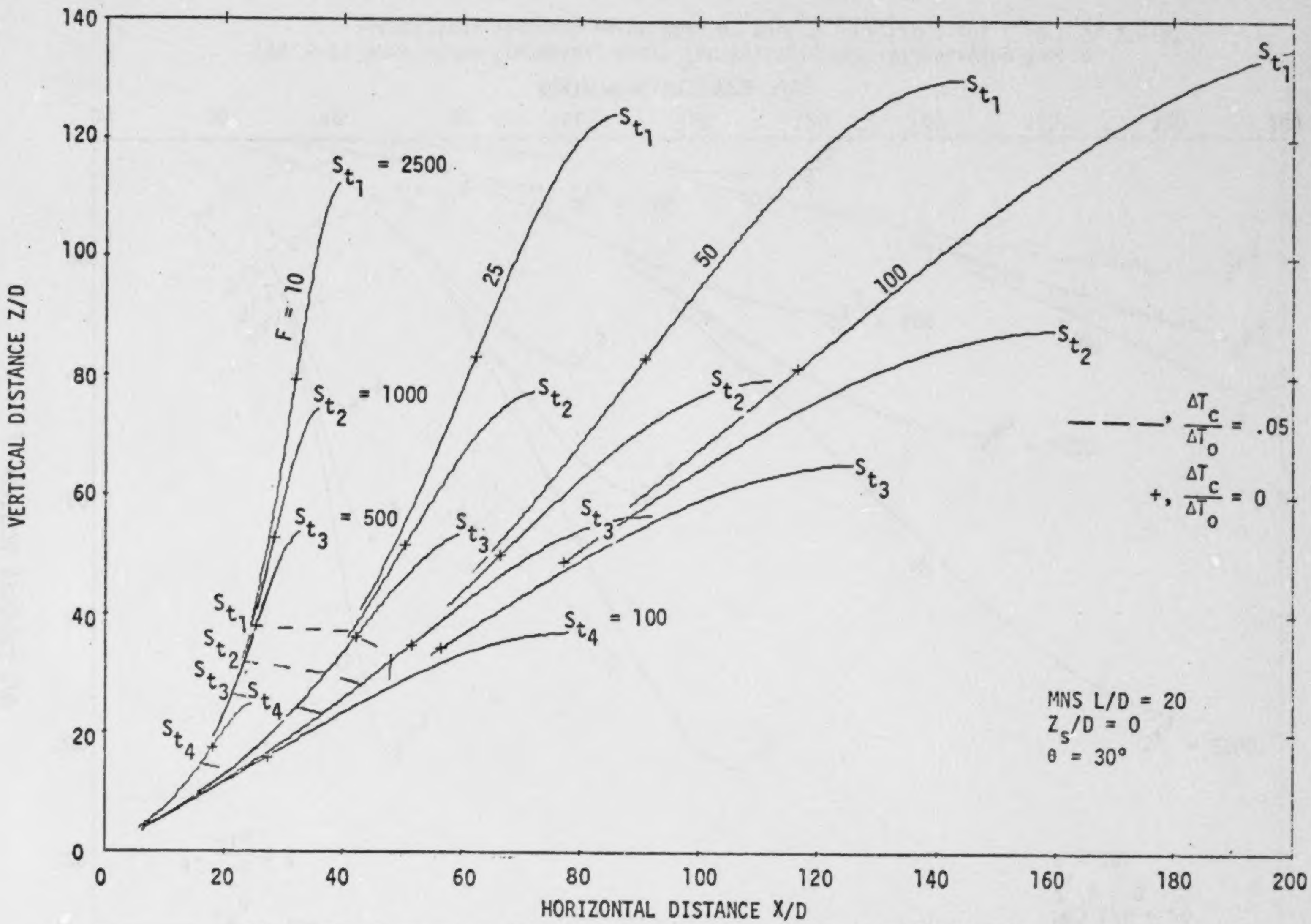

Fig. B-38 Temperature-Trajectory Chart for Multiple Jets Discharging into a Stratified, Stagnant Large Body of Water: MNS L/D = 20, Z_s/D = 0, Θ = 30°

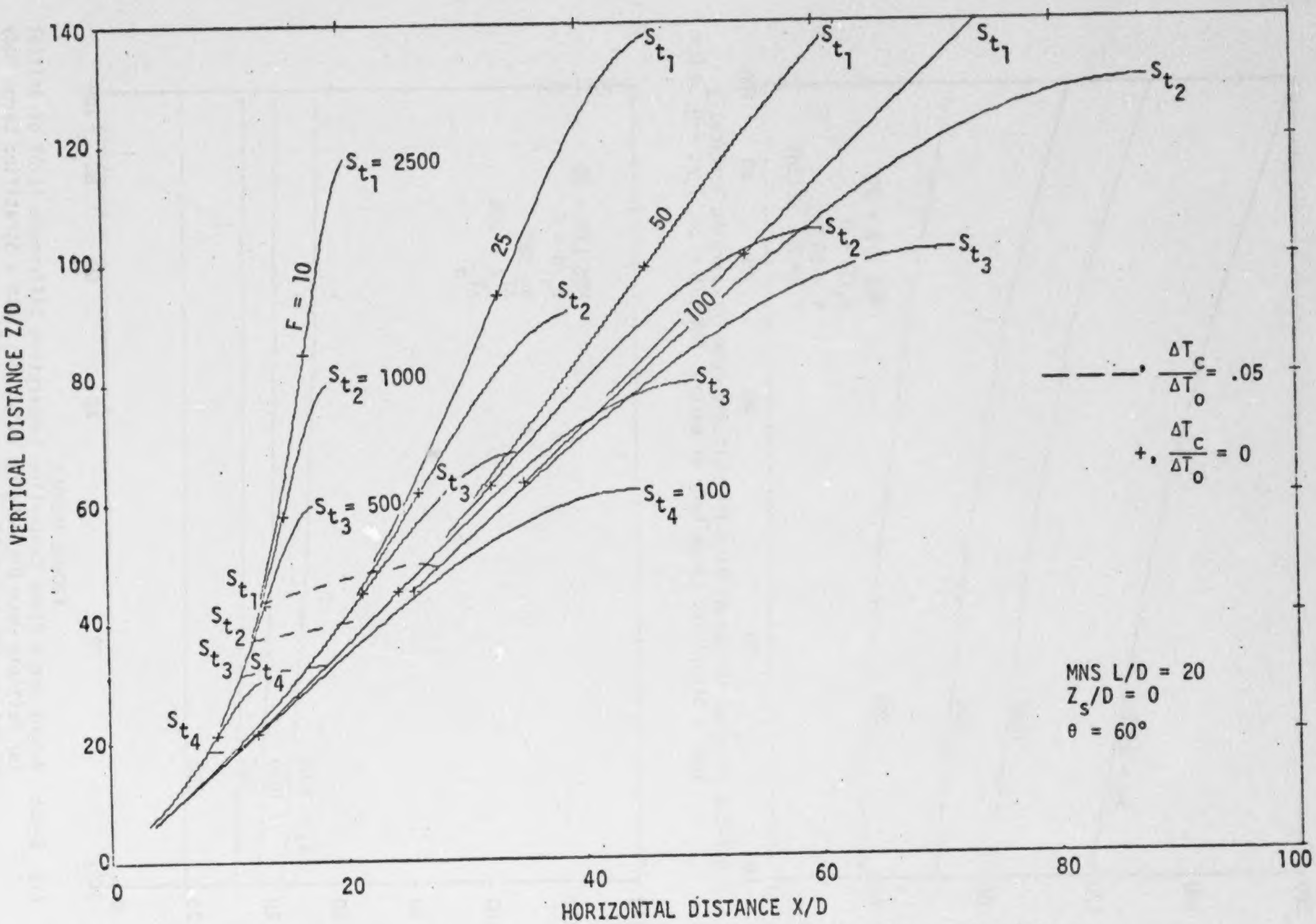

Fig.B-39 Temperature-Trajectory Chart for Multiple Jets Discharging into a Stratified, Stagnant Large Body of Water: MNS L/D = 20, $Z_s/D = 0$, Θ = 60°

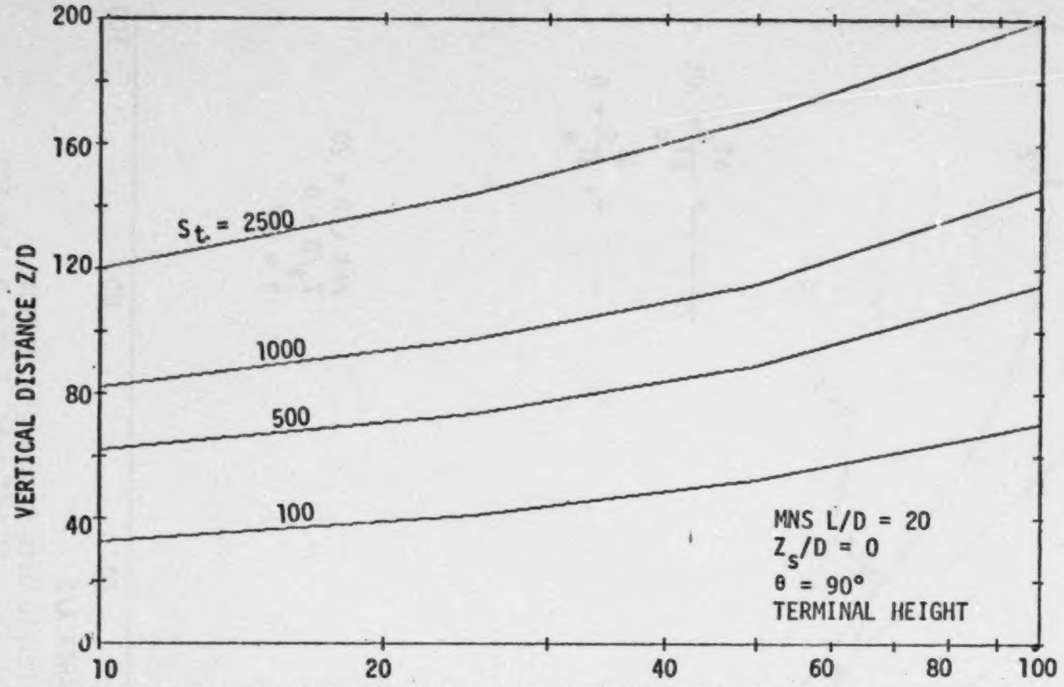

Fig.B-40a Terminal Height of Rise for Multiple Jets Discharging Vertically into a Stratified Large Body of Water: MNS L/D = 20, $Z_s/d = 0$, θ=90°

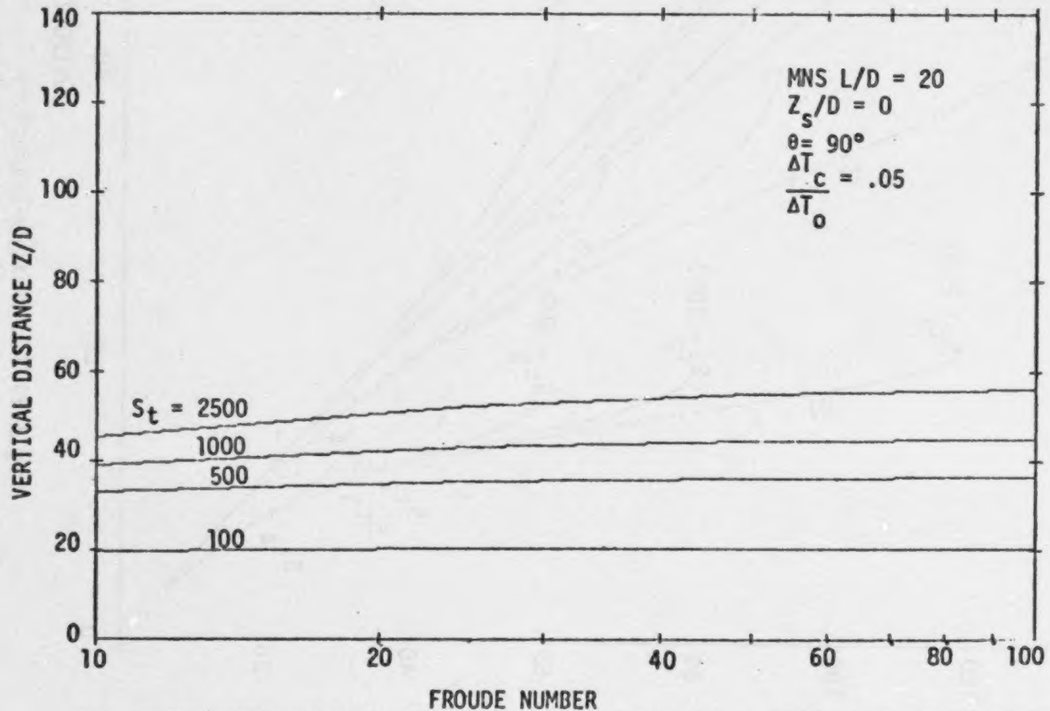

Fig. B-40b Height Where Plume Centerline Temperature Difference is 5% of Initial for Multiple Jets Discharging Vertically into a Stratified Large Body of Water: MNS L/D = 20, $Z_s/D = 0$, θ = 90°

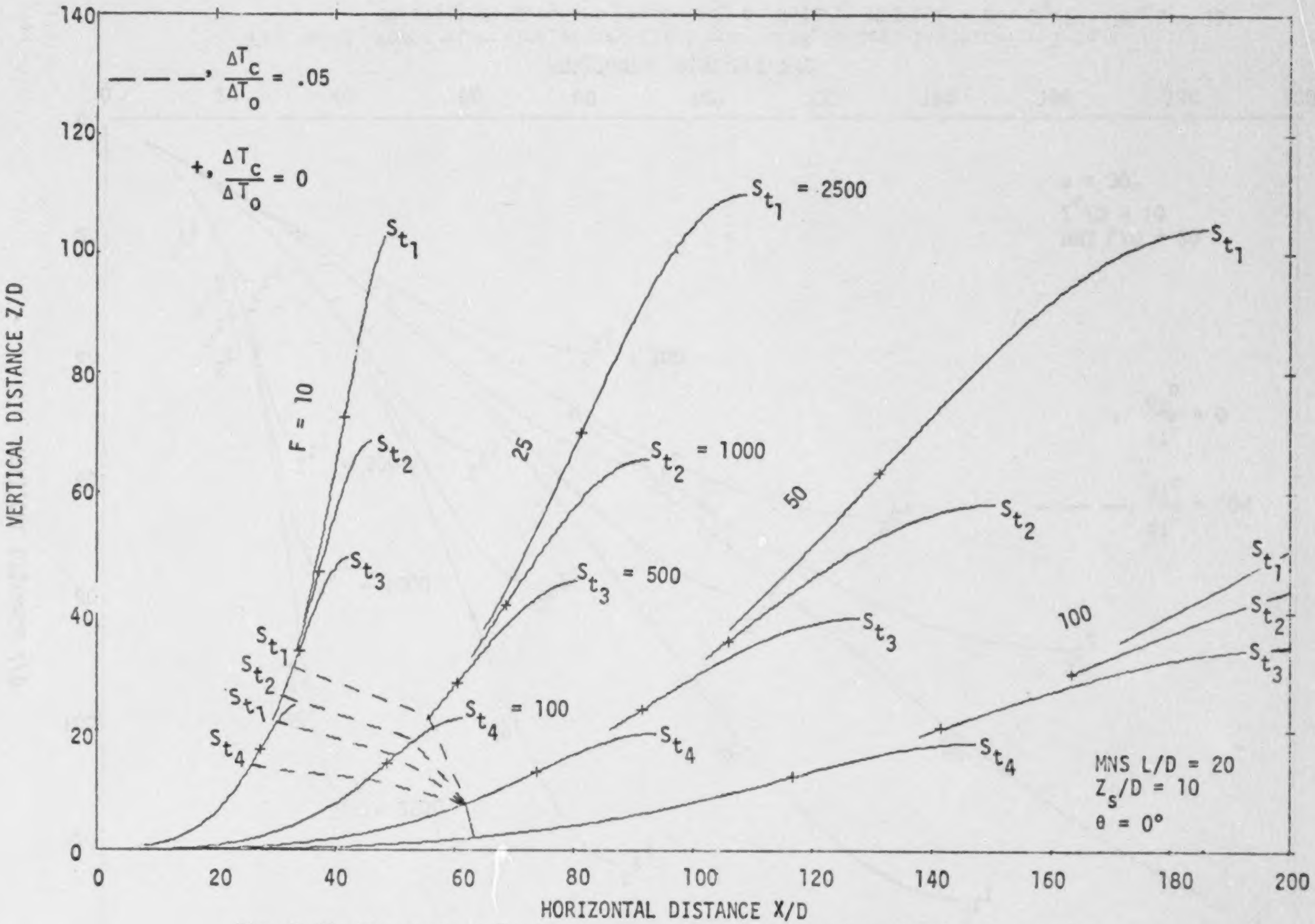

Fig. B-41 Temperature-Trajectory Chart for Multiple Jets Discharging into a Stratified, Stagnant Large Body of Water : MNS L/D = 20, $Z_s/D = 10$, $\Theta = 0°$

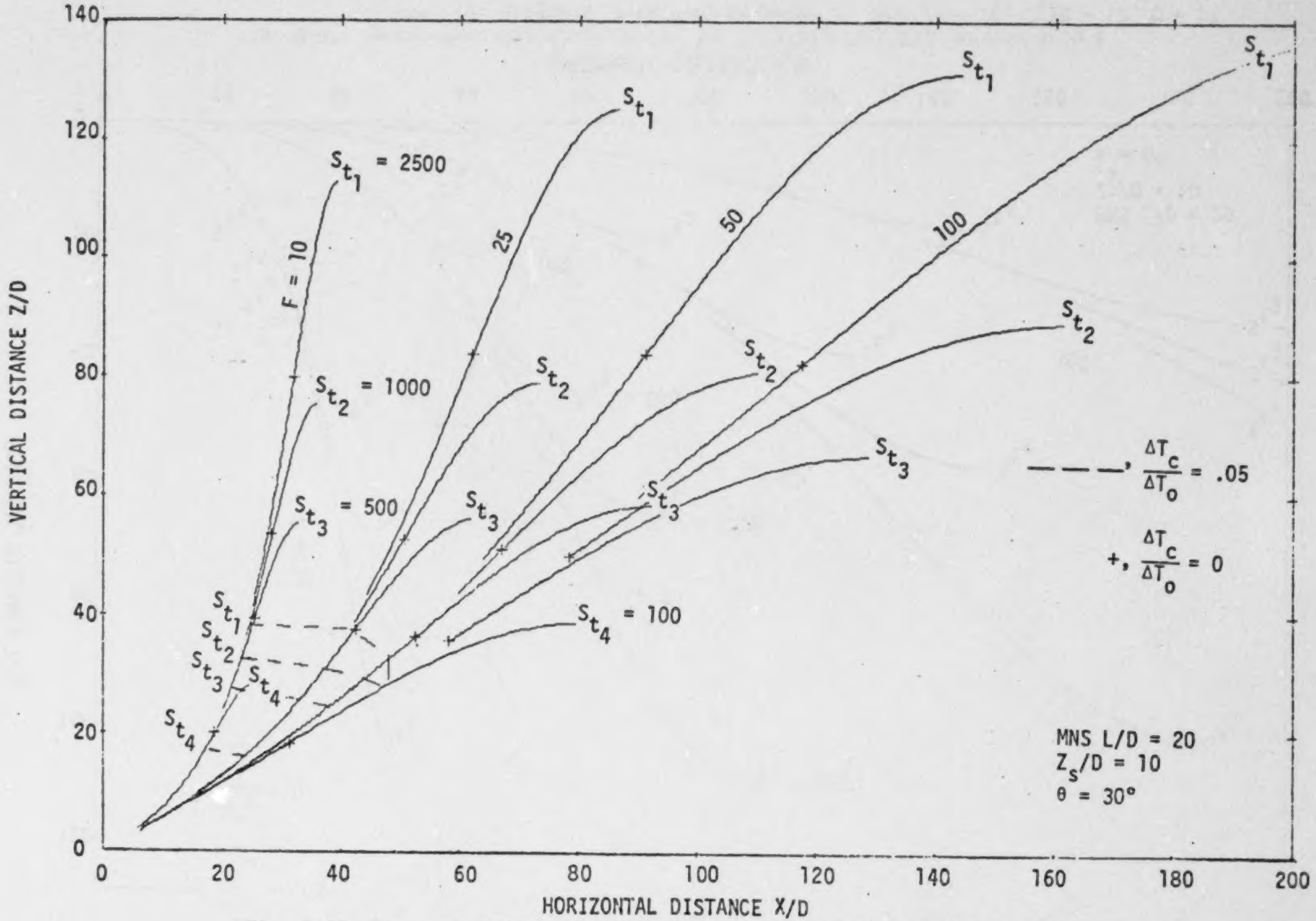

Fig. B-42 Temperature-Trajectory Chart for Multiple Jets Discharging into a Stratified, Stagnant Large Body of Water: MNS L/D = 20, $Z_s/D = 10$, Θ = 30°

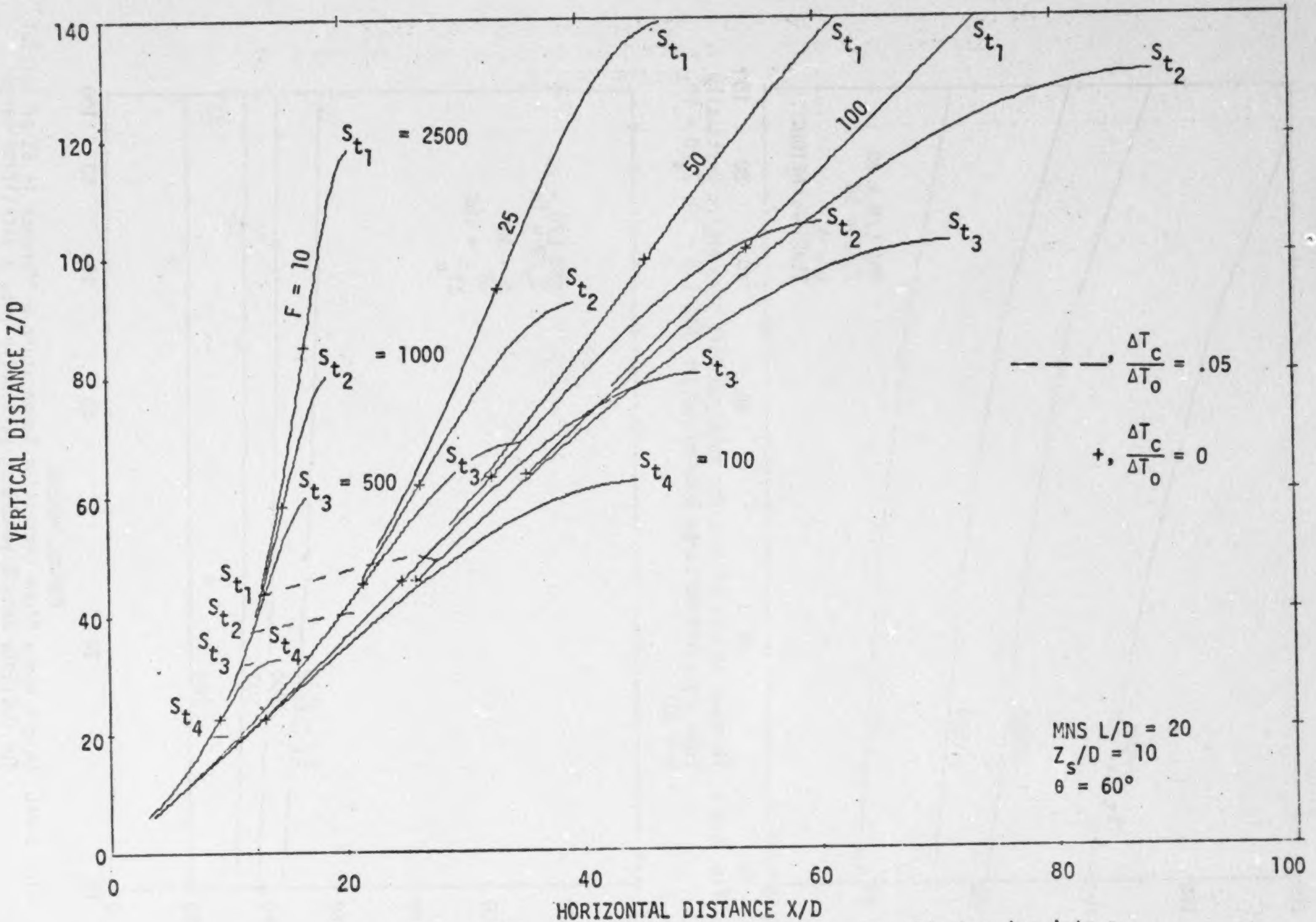

Fig. B-43 Temperature-Trajectory Chart for Multiple Jets Discharging into a Stratified, Stagnant Large Body of Water: MNS L/D = 20, Z_s/D = 10, Θ = 60°

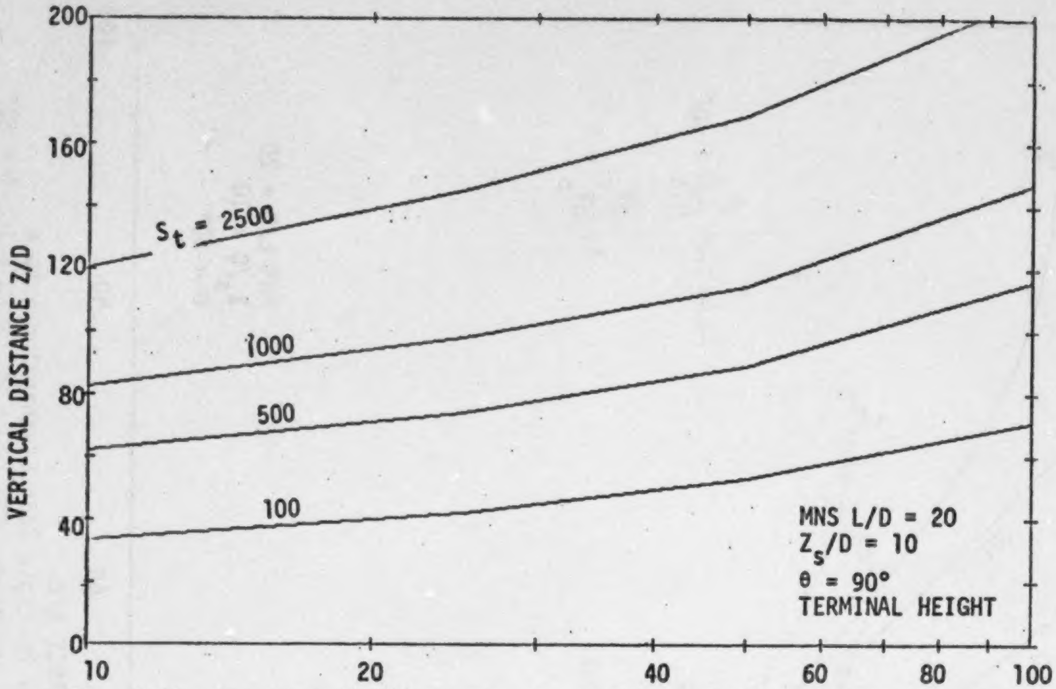

Fig. B-44a Terminal Height of Rise for Multiple Jets Discharging Vertically into a Stratified Large Body of Water: MNS L/D = 20, $Z_s/D = 10$, $\Theta = 90°$

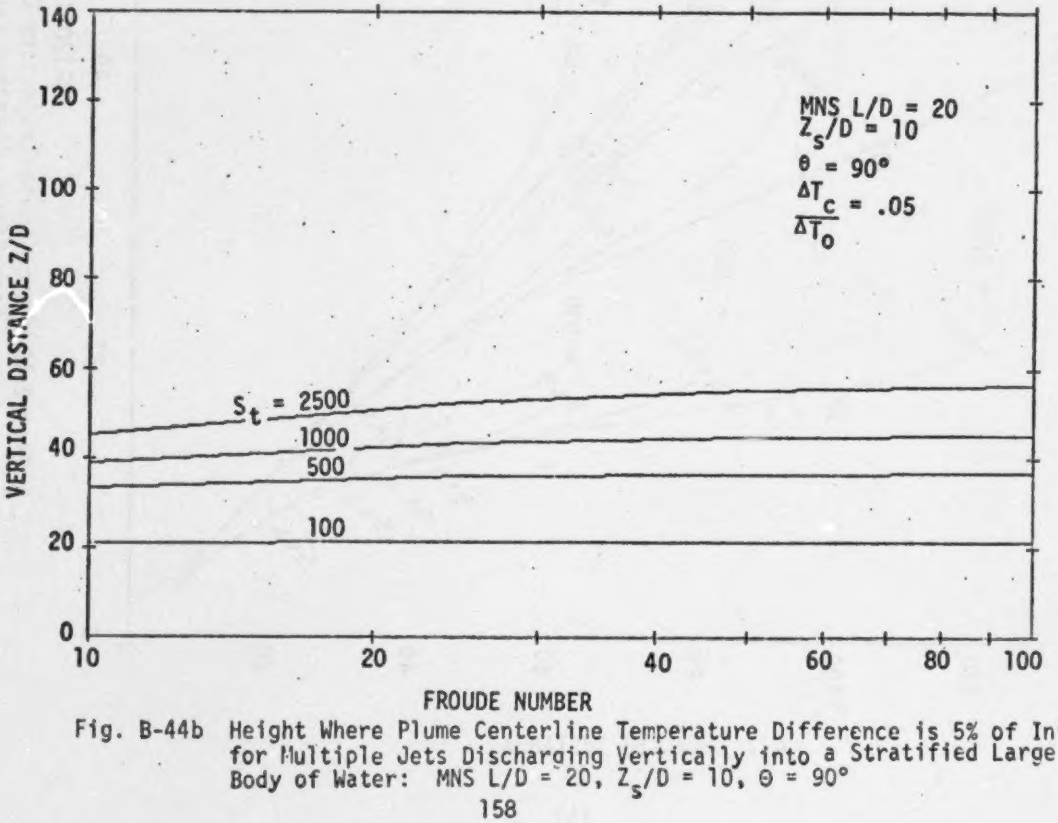

Fig. B-44b Height Where Plume Centerline Temperature Difference is 5% of Initial for Multiple Jets Discharging Vertically into a Stratified Large Body of Water: MNS L/D = 20, $Z_s/D = 10$, $\Theta = 90°$

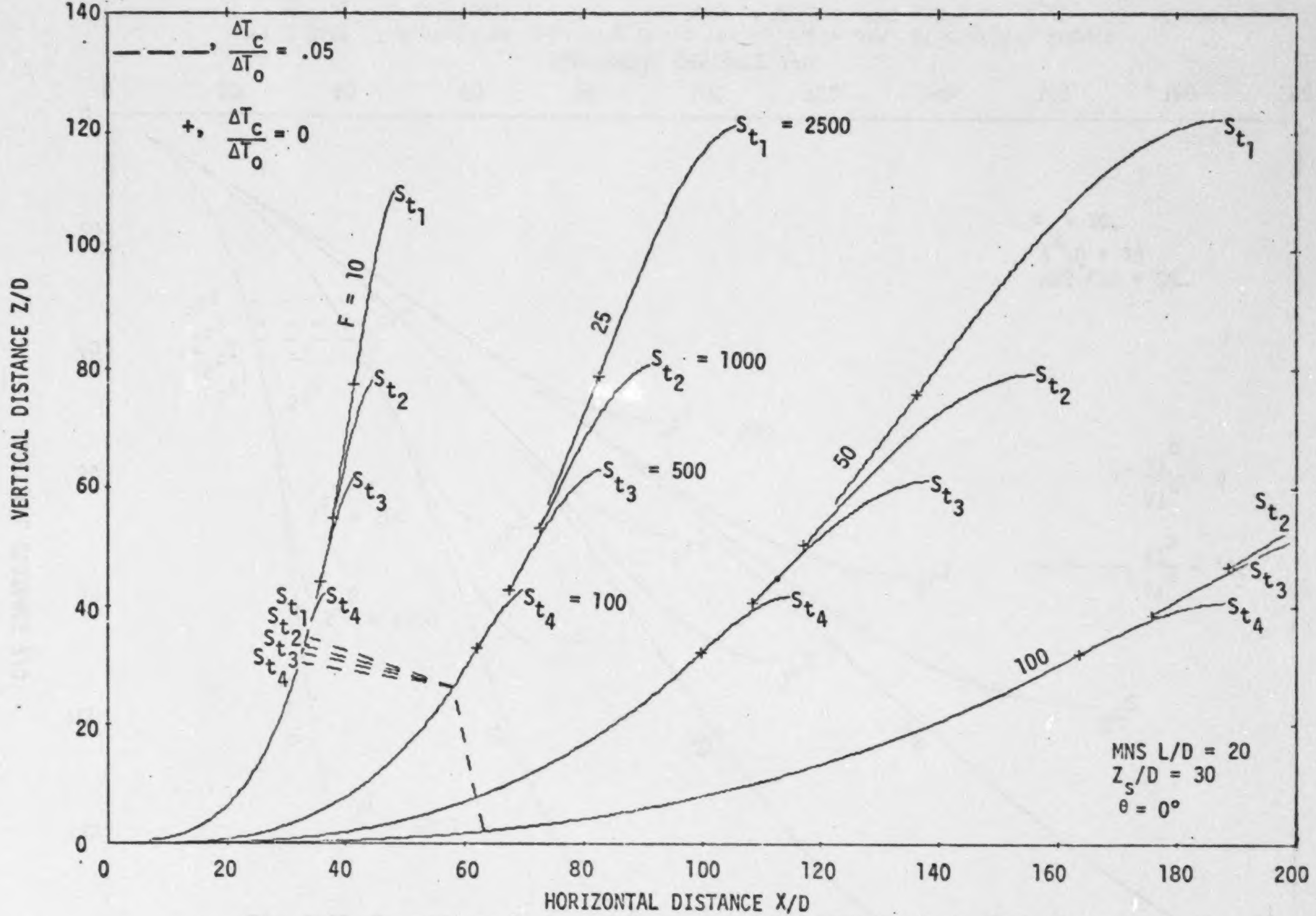

Fig. B-45 Temperature-Trajectory Chart for Multiple Jets Discharging into a Stratified, Stagnant Large Body of Water: MNS L/D = 20, $Z_s/D = 30$, $\Theta = 0°$

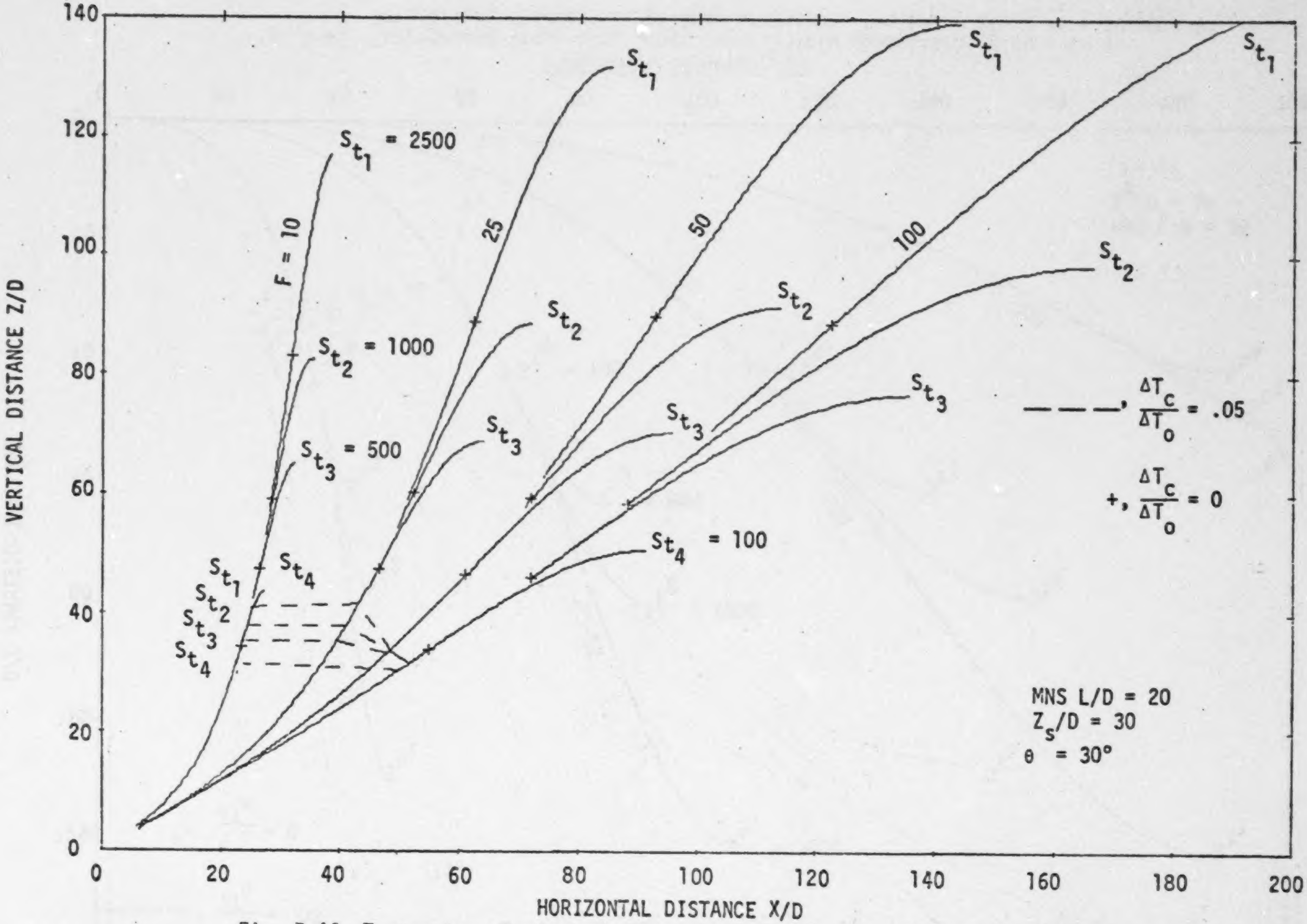

Fig. B-46 Temperature-Trajectory Chart for Multiple Jets Discharging into a Stratified, Stagnant Large Body of Water: MNS L/D = 20, Z_s/D = 30, Θ = 30°

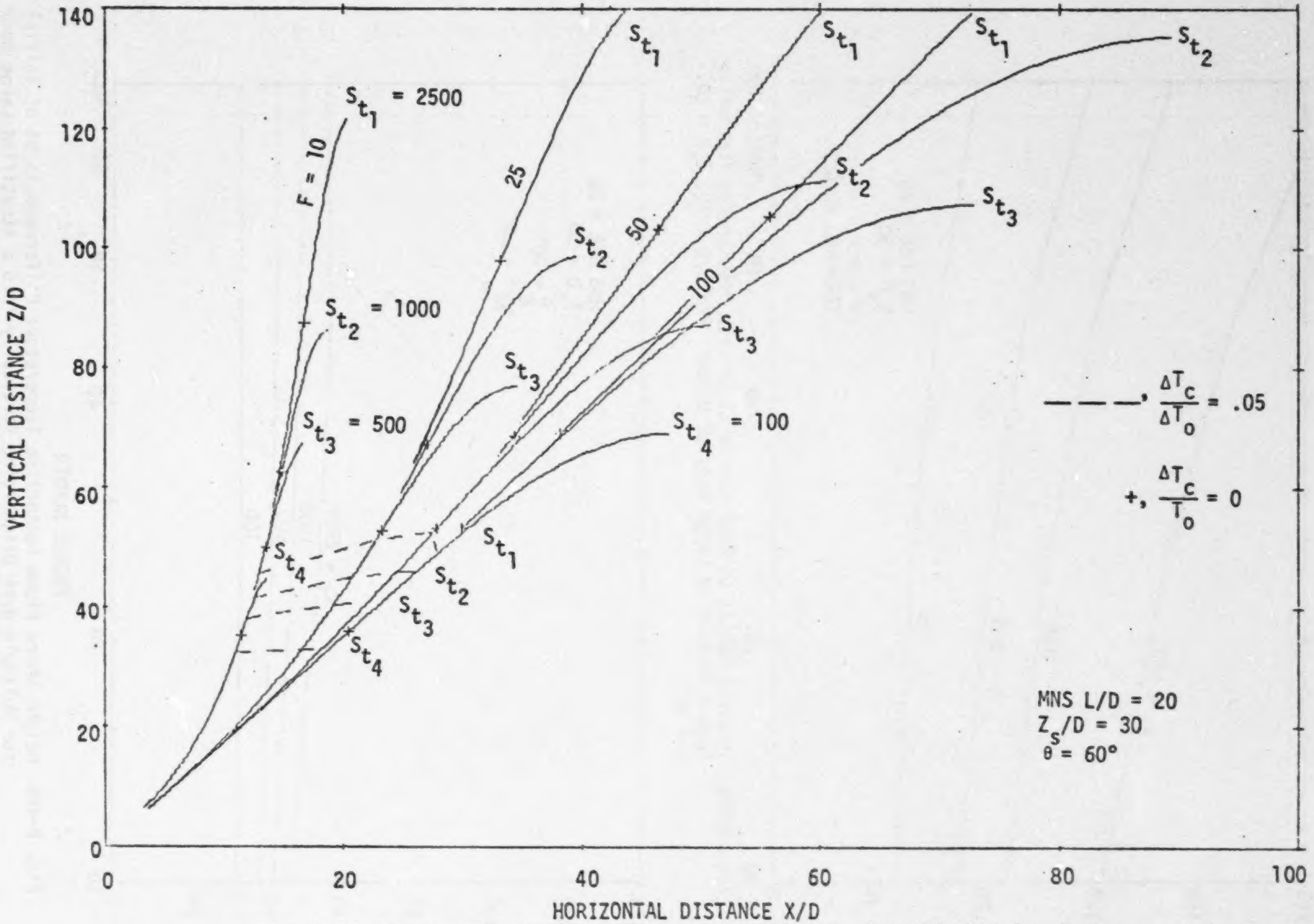

Fig. B-47 Temperature-Trajectory Chart for Multiple Jets Discharging into a Stratified, Stagnant Large Body of Water: MNS L/D = 20, Z_s/D = 30, Θ = 60°

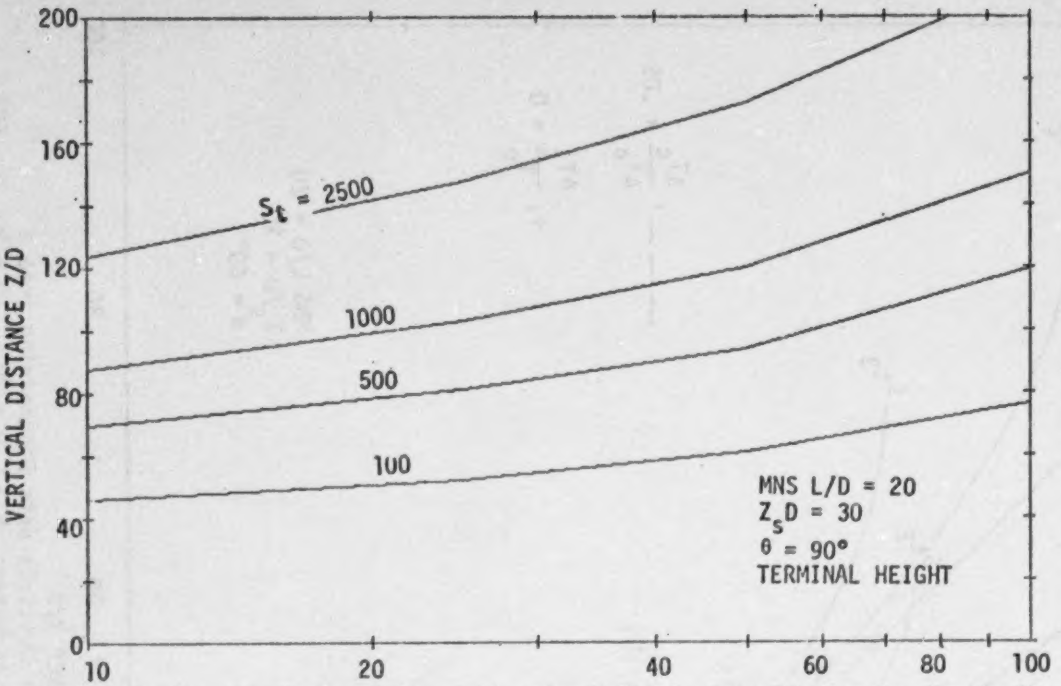

Fig. B-48a Terminal Height of Rise for Multiple Jets Discharging Vertically into a Stratified Large Body of Water: MNS L/D = 20, Z_sD = 30, θ = 90°

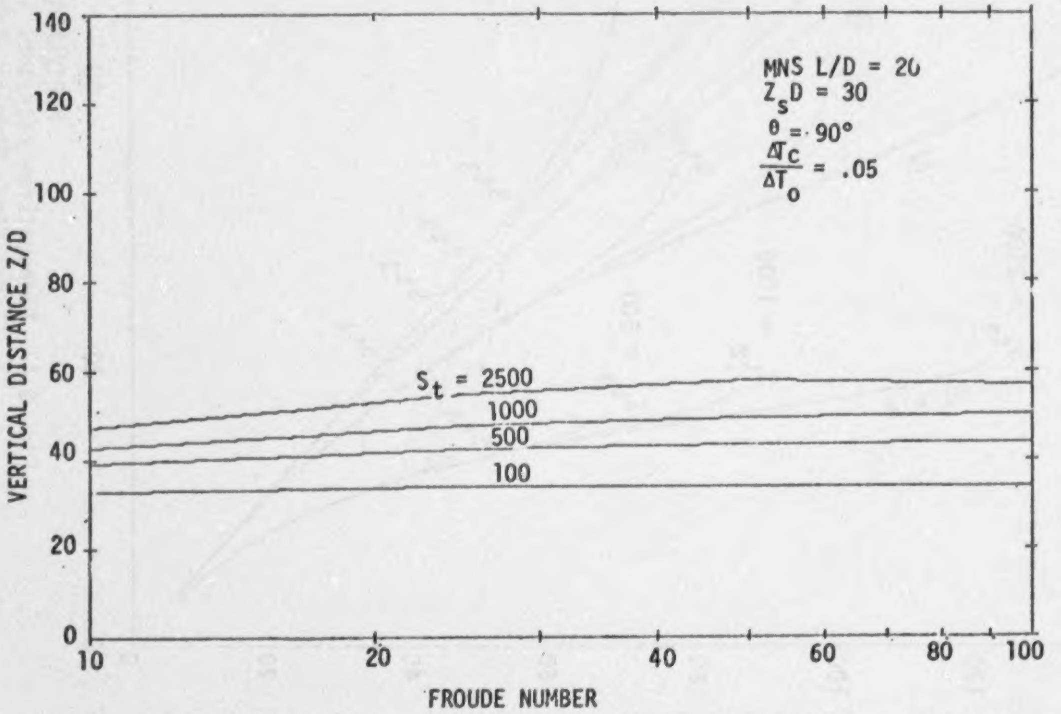

Fig. B-48b Height Where Plume Centerline Temperature Difference is 5% of Initial for Multiple Jets Discharging Vertically into a Stratified Large Body of Water: MNS L/D = 20, Z_sD = 30, Θ = 90°

APPENDIX C

Nomograms for Discharge into Moving, Non-Stratified Water, (RCN)

TABLE III

Figure Numbers Corresponding to Plume Behavior From Single Port Submerged Diffusers Discharging into Moving, Non-stratified Water

	Discharge Angle			
k	Co-flow Θ=0°	Cross-flow Θ=90°	Θ=30°	Θ=60°
0.5	C-1,2			
1	C-3,4			
2	C-5,6	C-19,20	C-11,12	C-15,16
4	C-7,8	C-21,22	C-13,14	C-17,18
6	C-9,10	C-23,24		
8		C-25,26		
12		C-27,28		
16		C-29,30		

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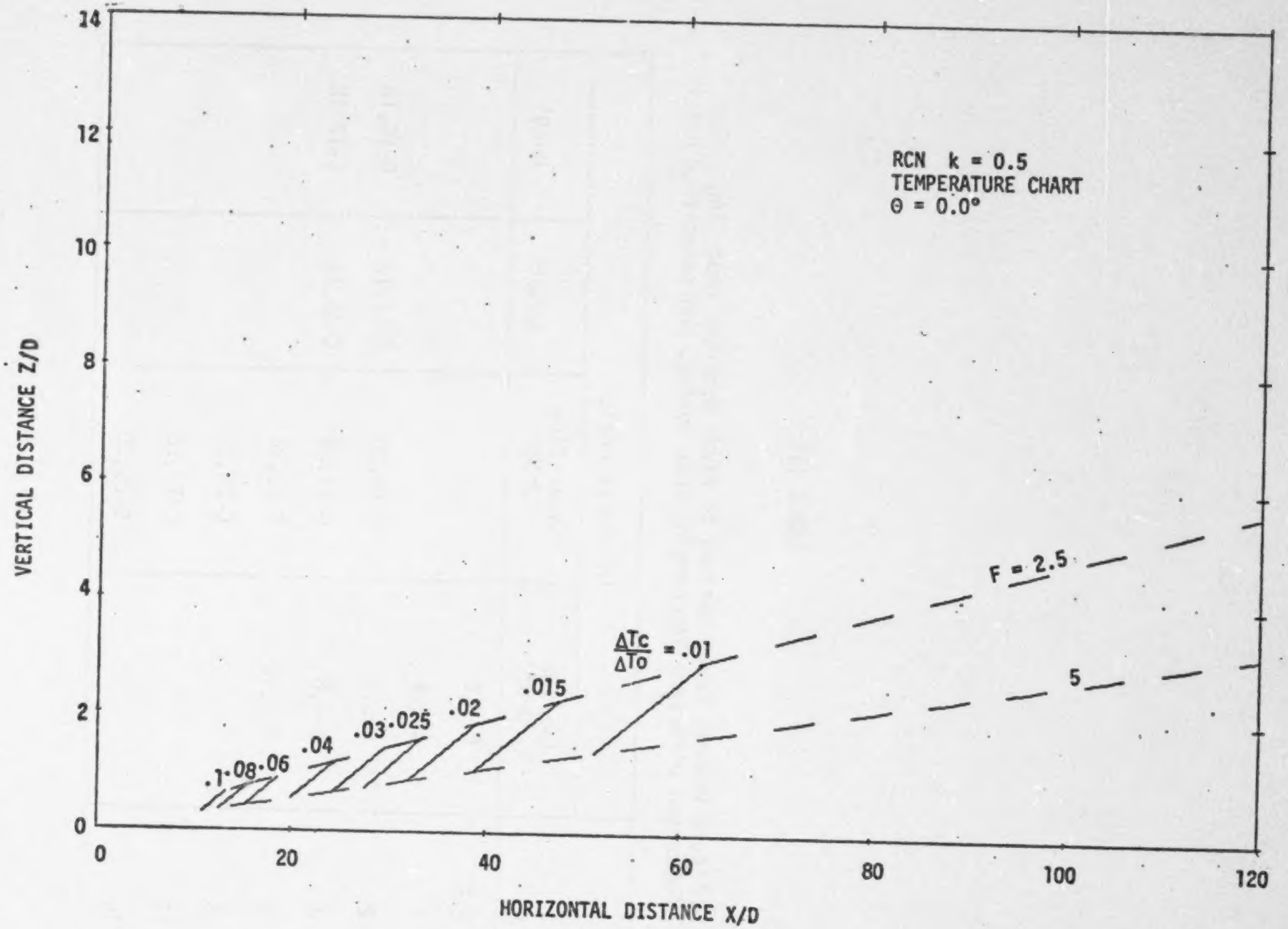

Fig. C-1 Temperature-Trajectory Chart for a Single Jet Discharging into a Non-Stratified, Moving Large Body of Water: RCN k = 0.5, Θ = 0.0°

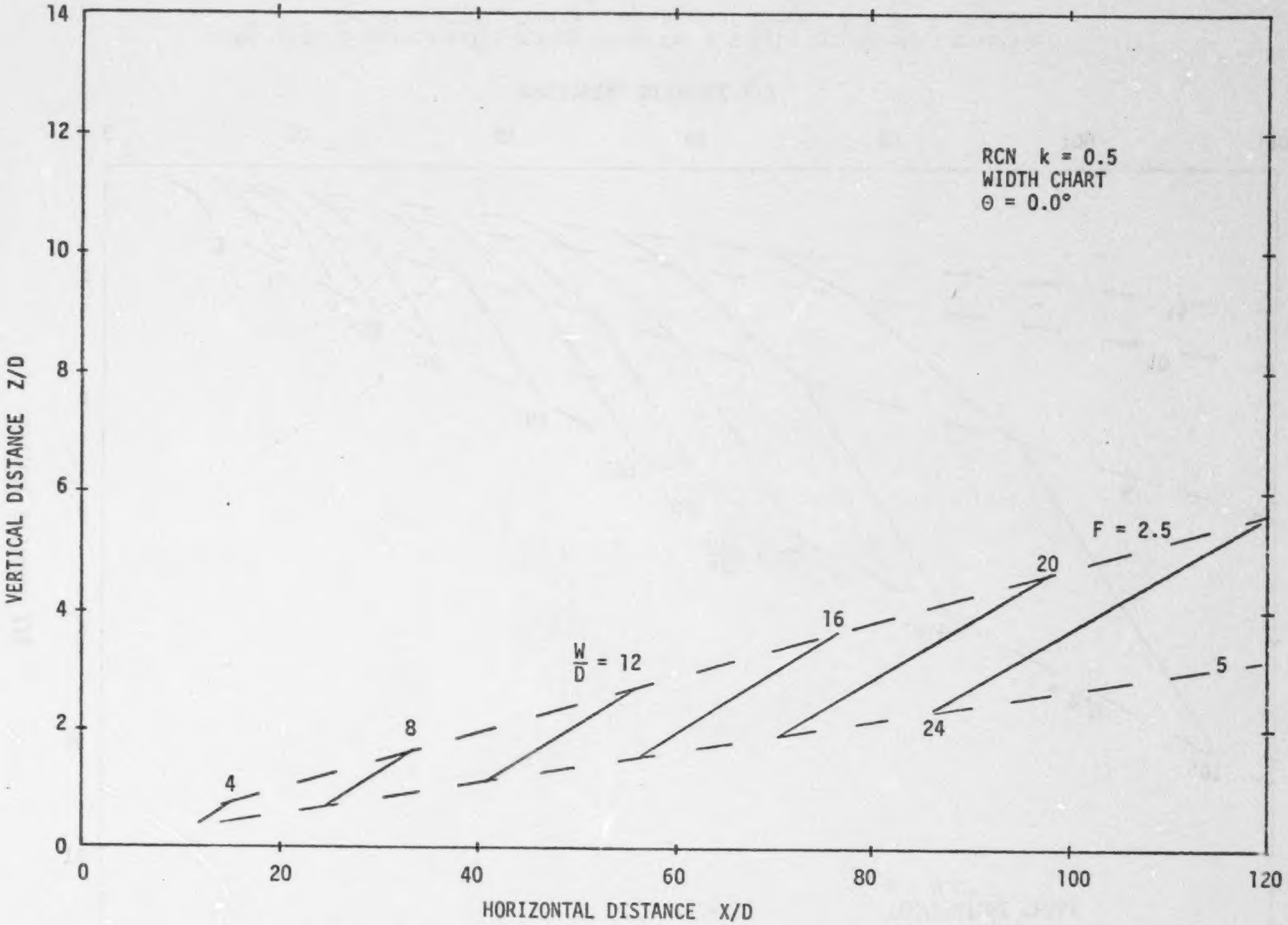

Fig. C-2 Width-Trajectory Chart for a Single Jet Discharging into a Non-Stratified, Moving Large Body of Water: RCN k = 0.5, Θ = 0.0°

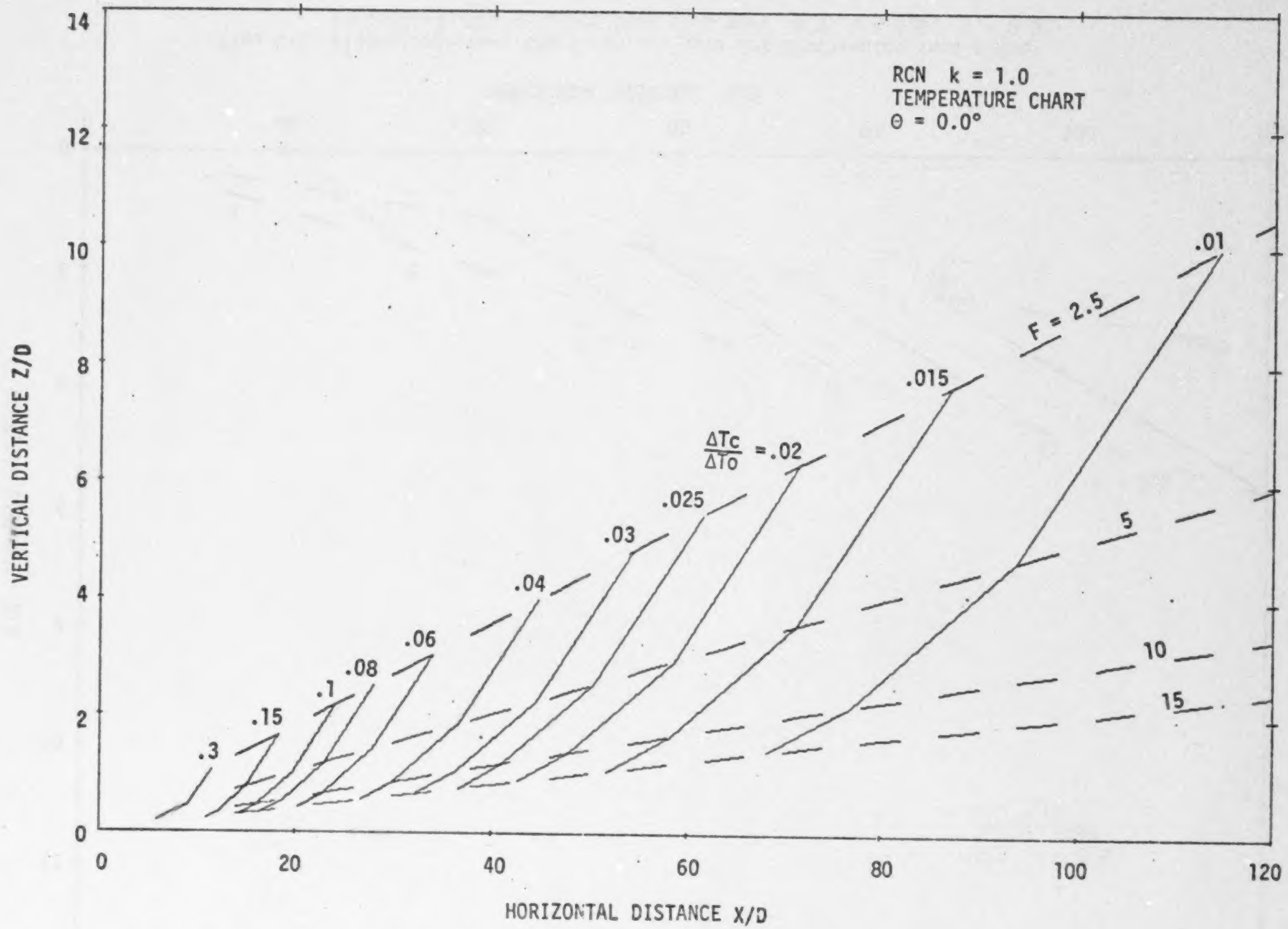

Fig. C-3 Temperature-Trajectory Chart for a Single Jet Discharing into a Non-Stratified, Moving Large Body of Water: RCN k = 1, Θ = 0°

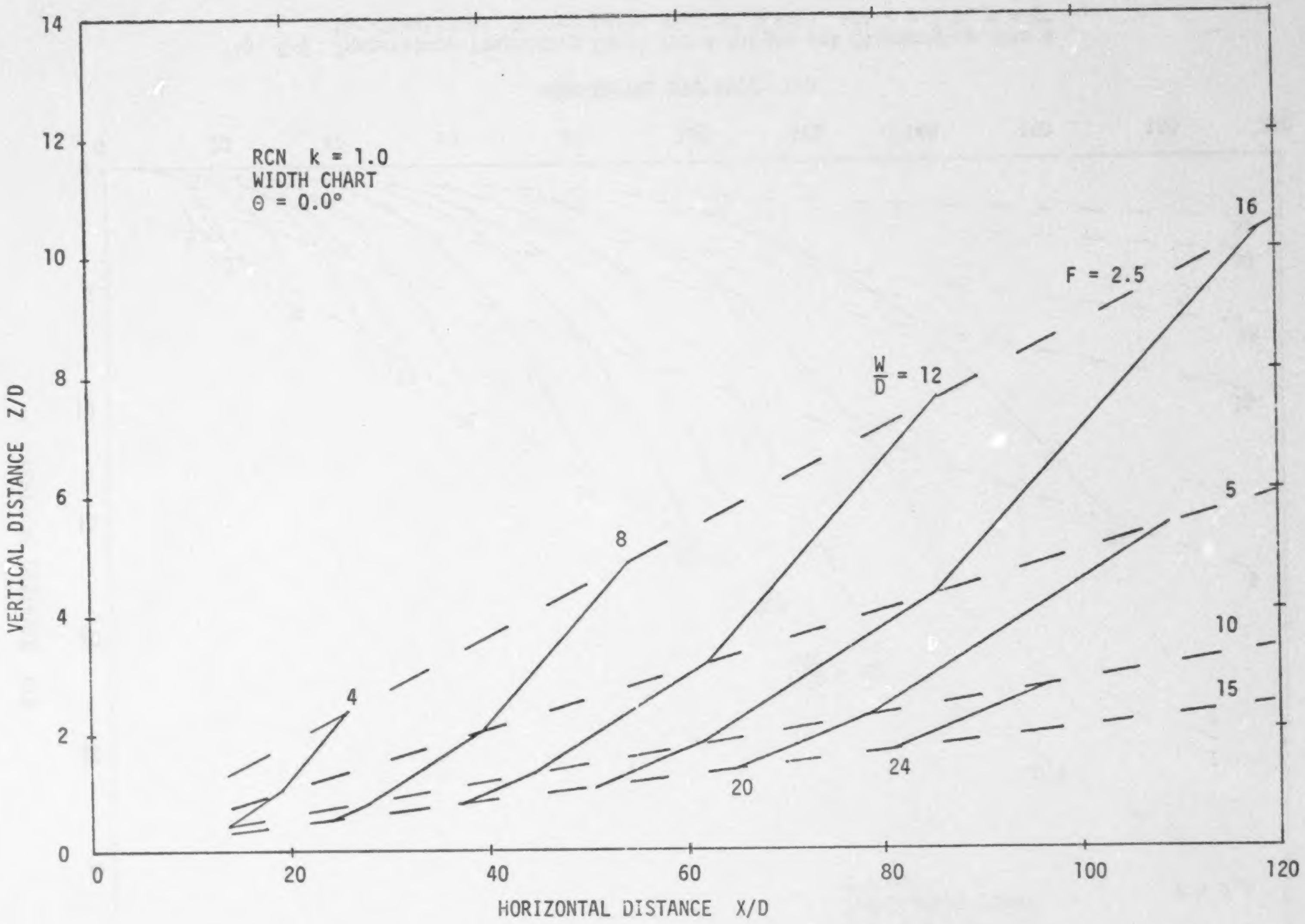

Fig. C-4 Width-Trajectory Chart for a Single Jet Discharging into a Non-Stratified, Moving Large Body of Water: RCN k = 1.0, Θ = 0.0°

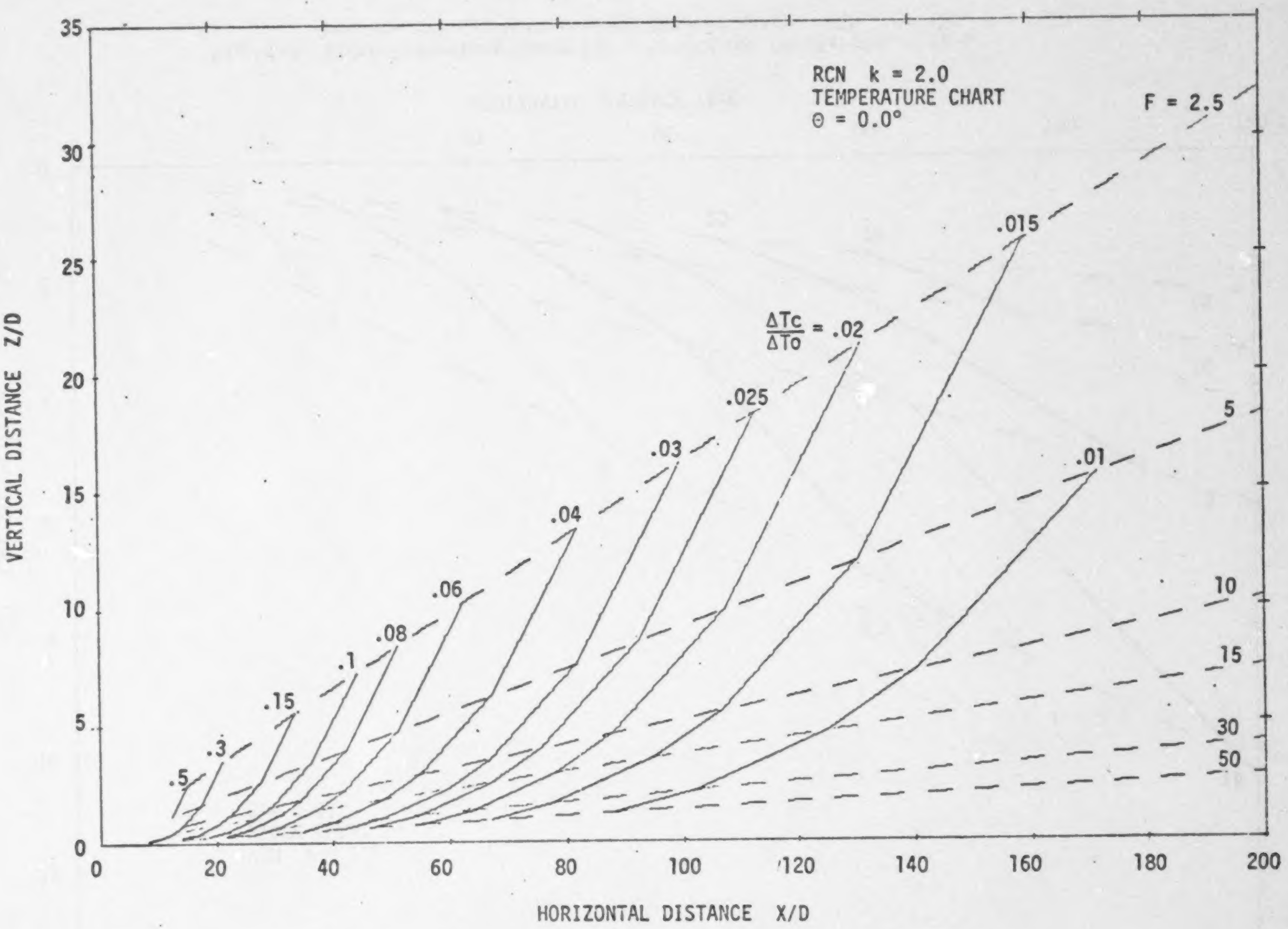

Fig. C-5 Temperature-Trajectory Chart for a Single Jet Discharging into a Non-Stratified, Moving Large Body of Water: RCN k = 2.0, Θ = 0°

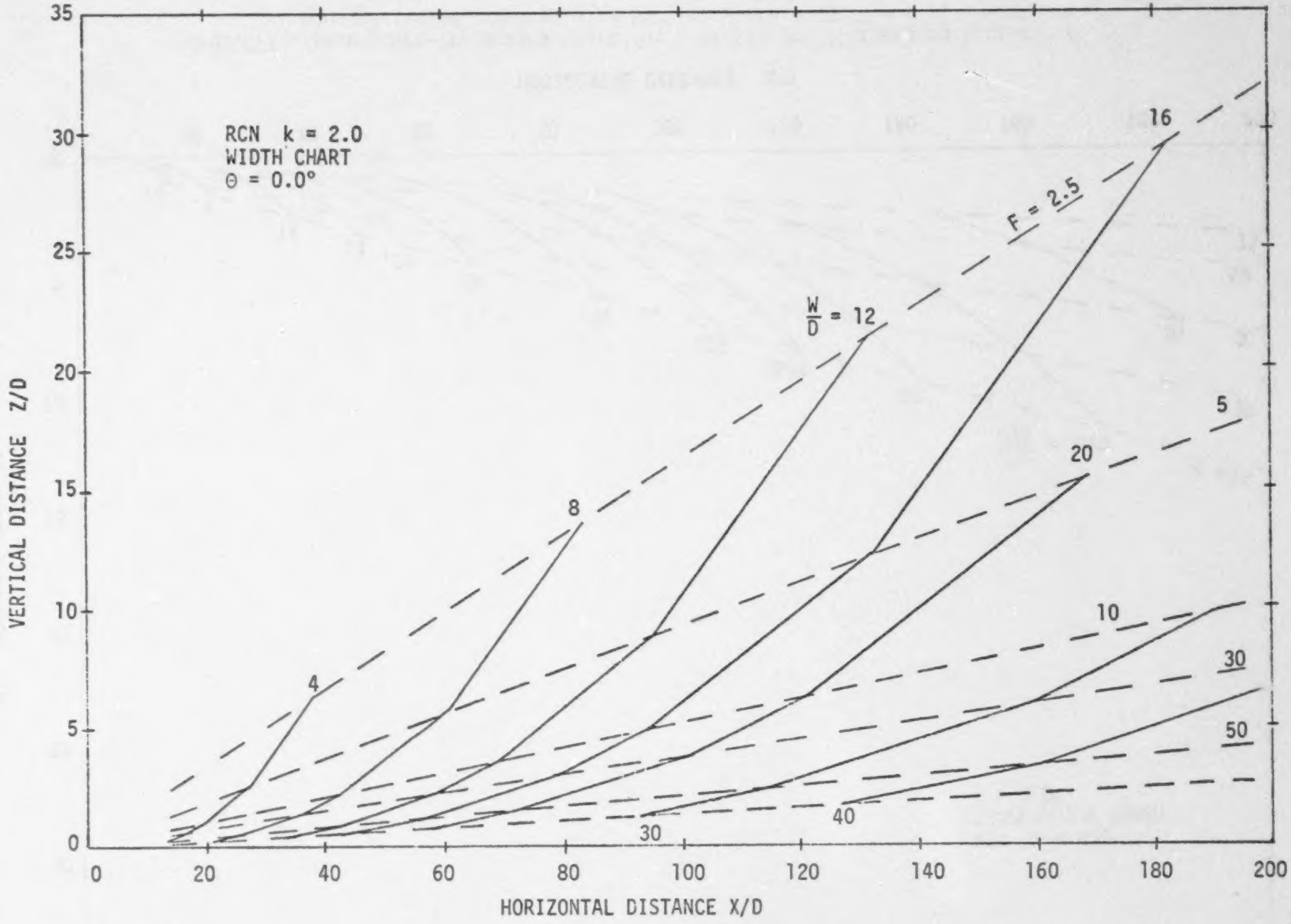

Fig. C-6 Width-Trajectory Chart for a Single Jet Discharging into a Non-Stratified, Moving Large Body of Water: RCN k = 2.0, Θ = 0.0°

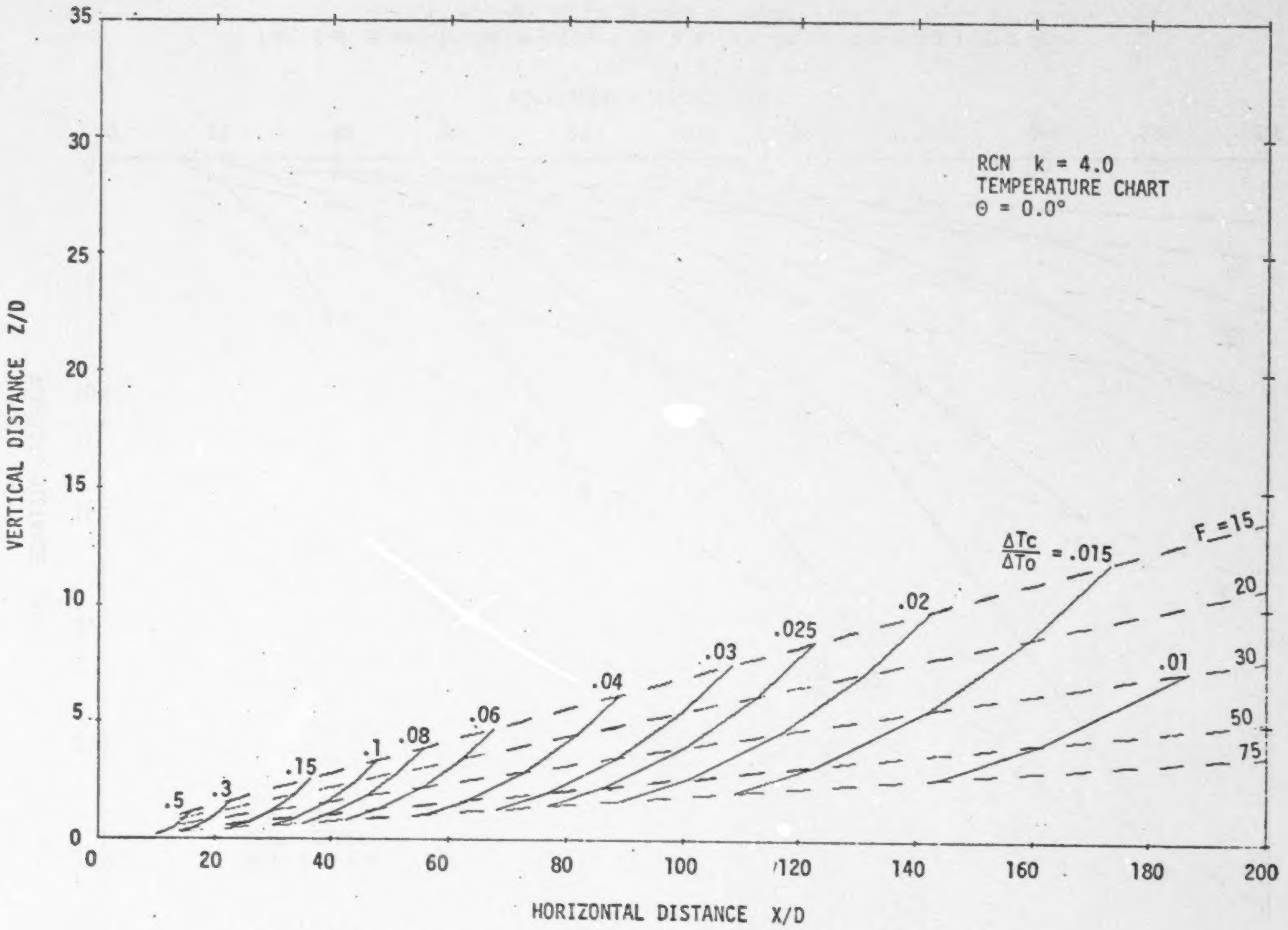

Fig. C-7 Temperature-Trajectory Chart for a Single Jet Discharging into a Non-Stratified, Moving Large Body of Water: RCN k = 4.0, Θ = 0°

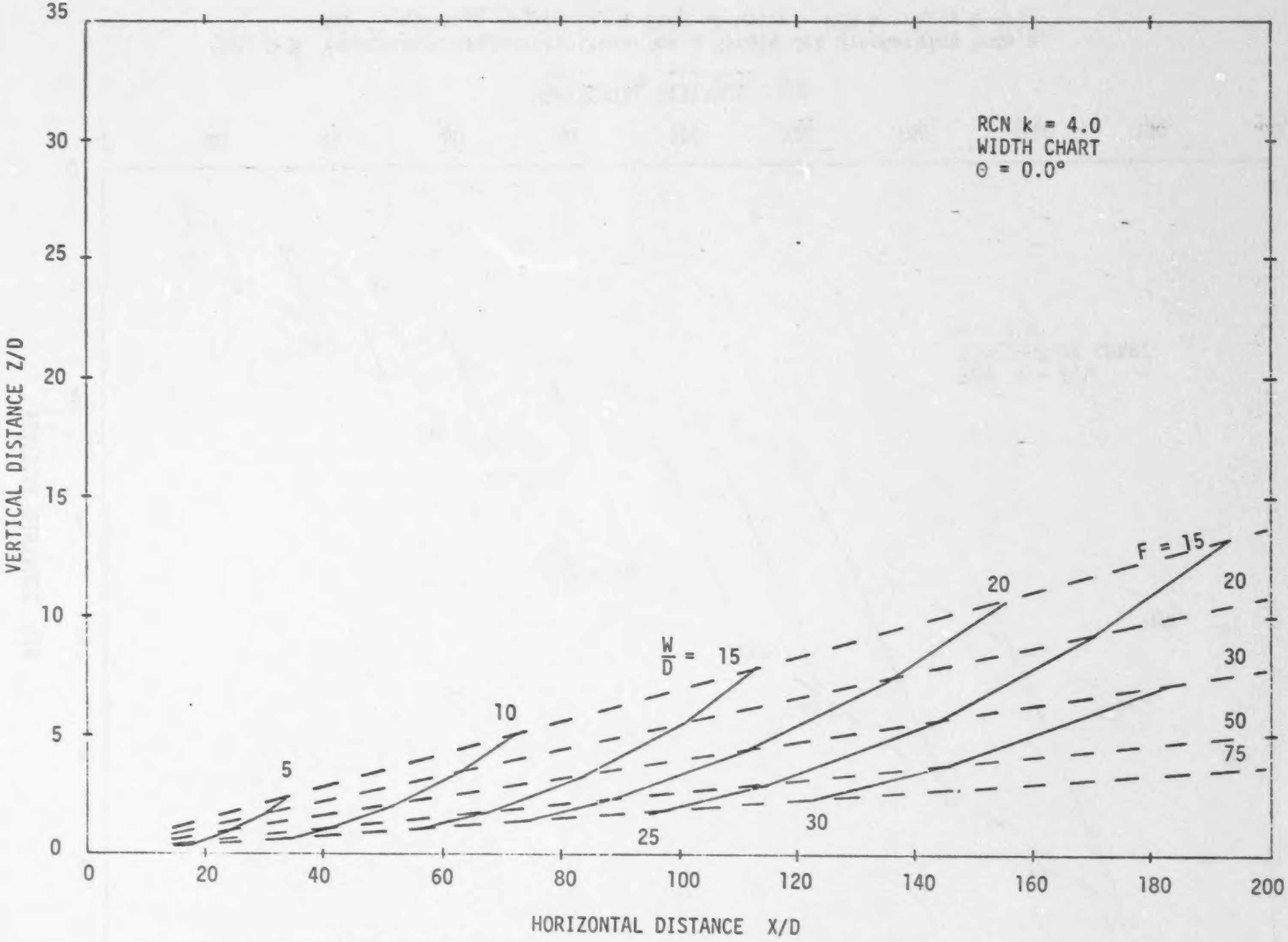

Fig. C-8 Width-Trajectory Chart for a Single Jet Discharging into a Non-Stratified, Moving Large Body of Water: RCN k = 4.0, Θ = 0.0°

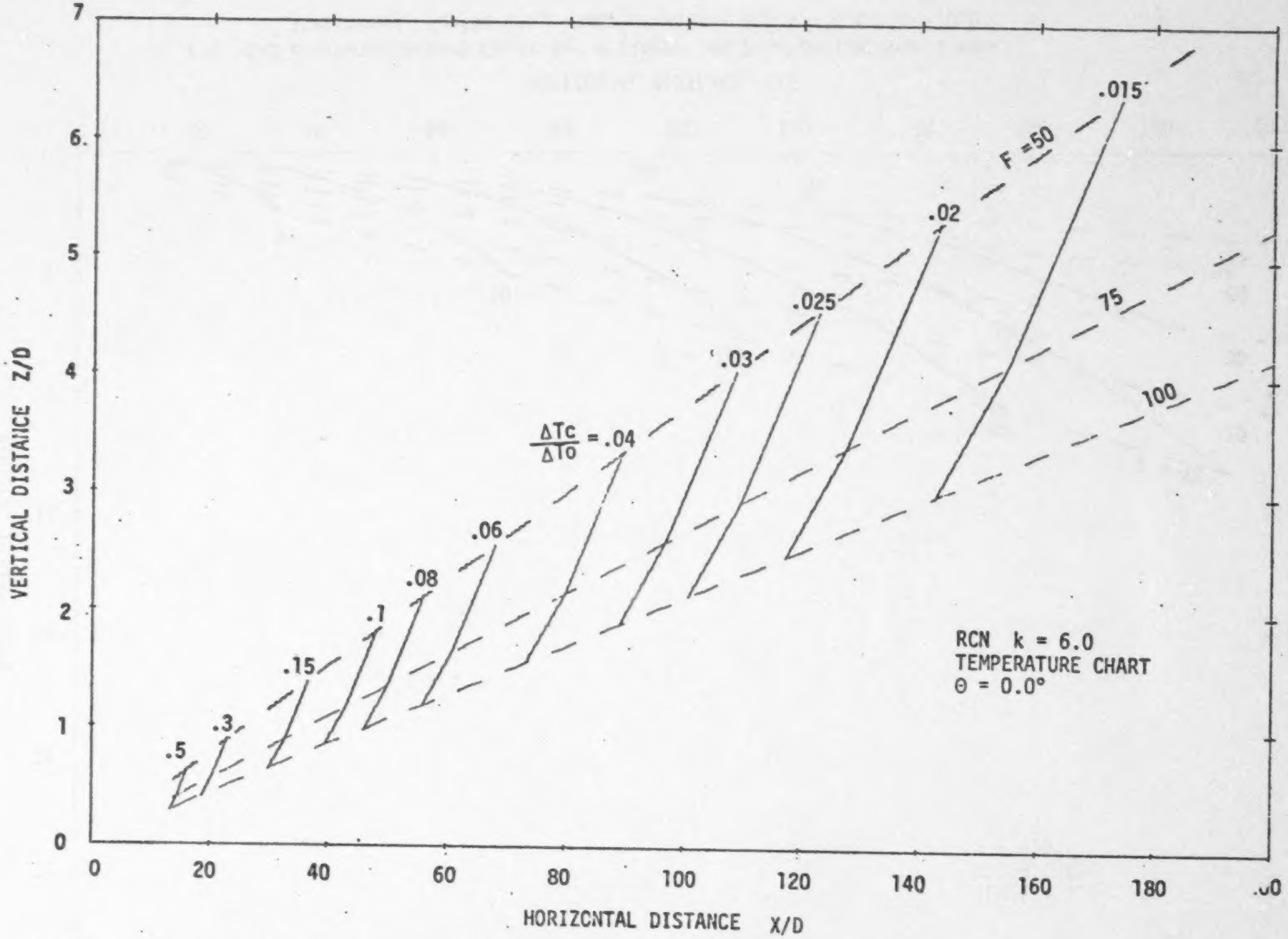

Fig. C-9 Temperature-Trajectory Chart for a Single Jet Discharging into a Non-Stratified, Moving Large Body of Water: RCN k = 6.0, Θ = 0°

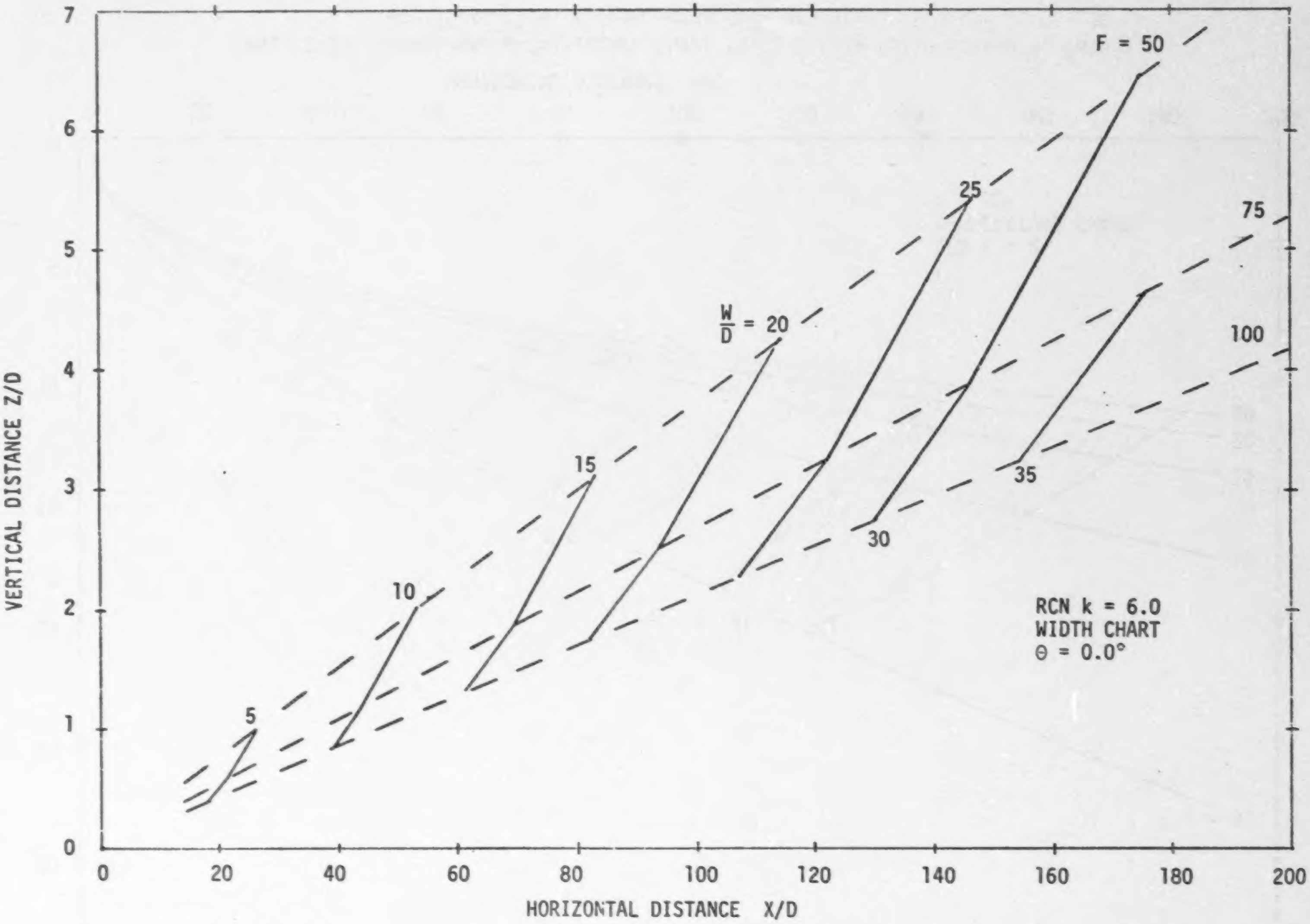

Fig. C-10 Width-Trajectory Chart for a Single Jet Discharging into a Non-Stratified, Moving Large Body of Water: RCN k = 6.0, Θ = 0.0°

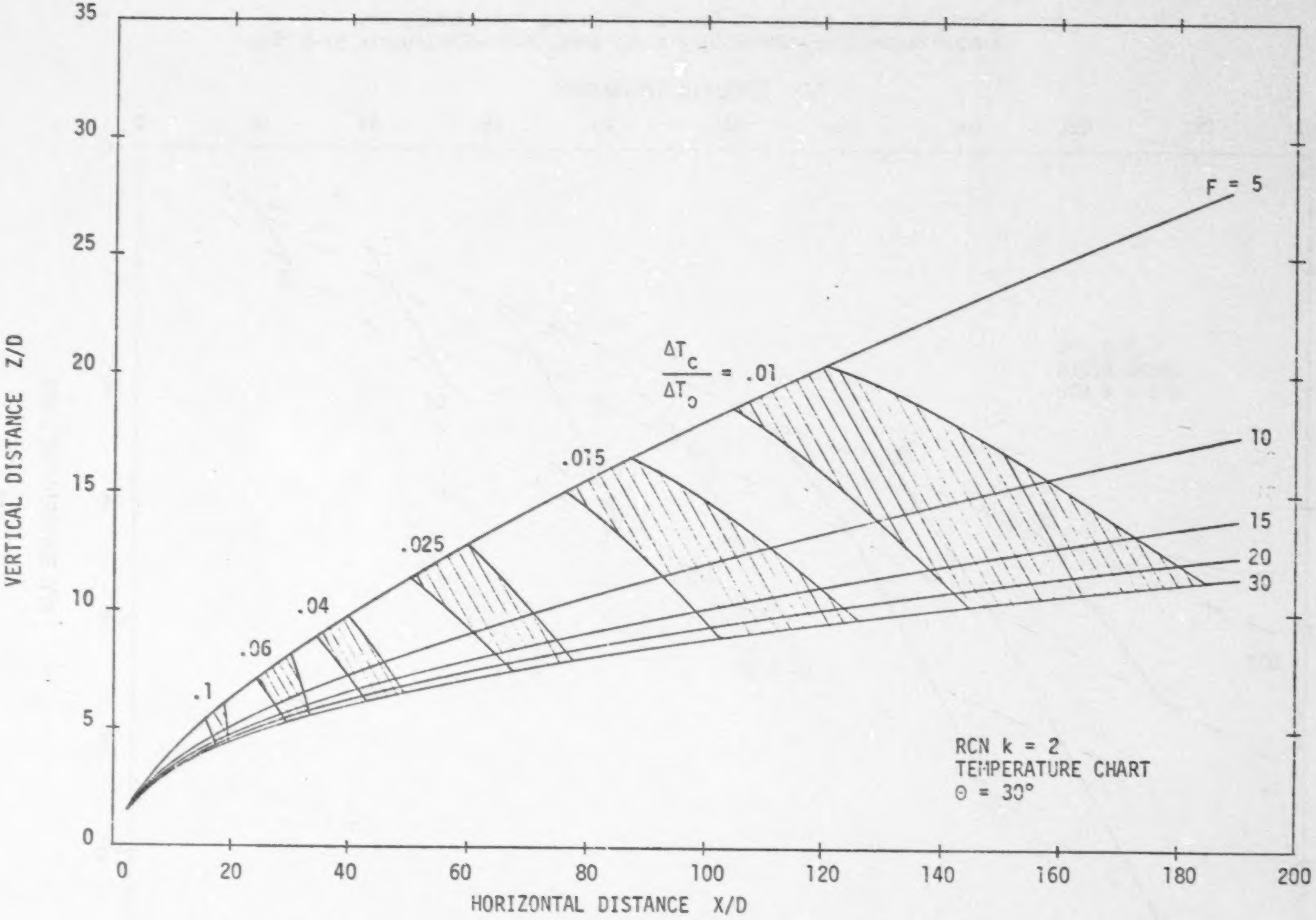

Fig. C-11 Temperature-Trajectory Chart for a Single Jet Discharging into a Non-Stratified, Moving Large Body of Water: RCN k = 2, Θ = 30°

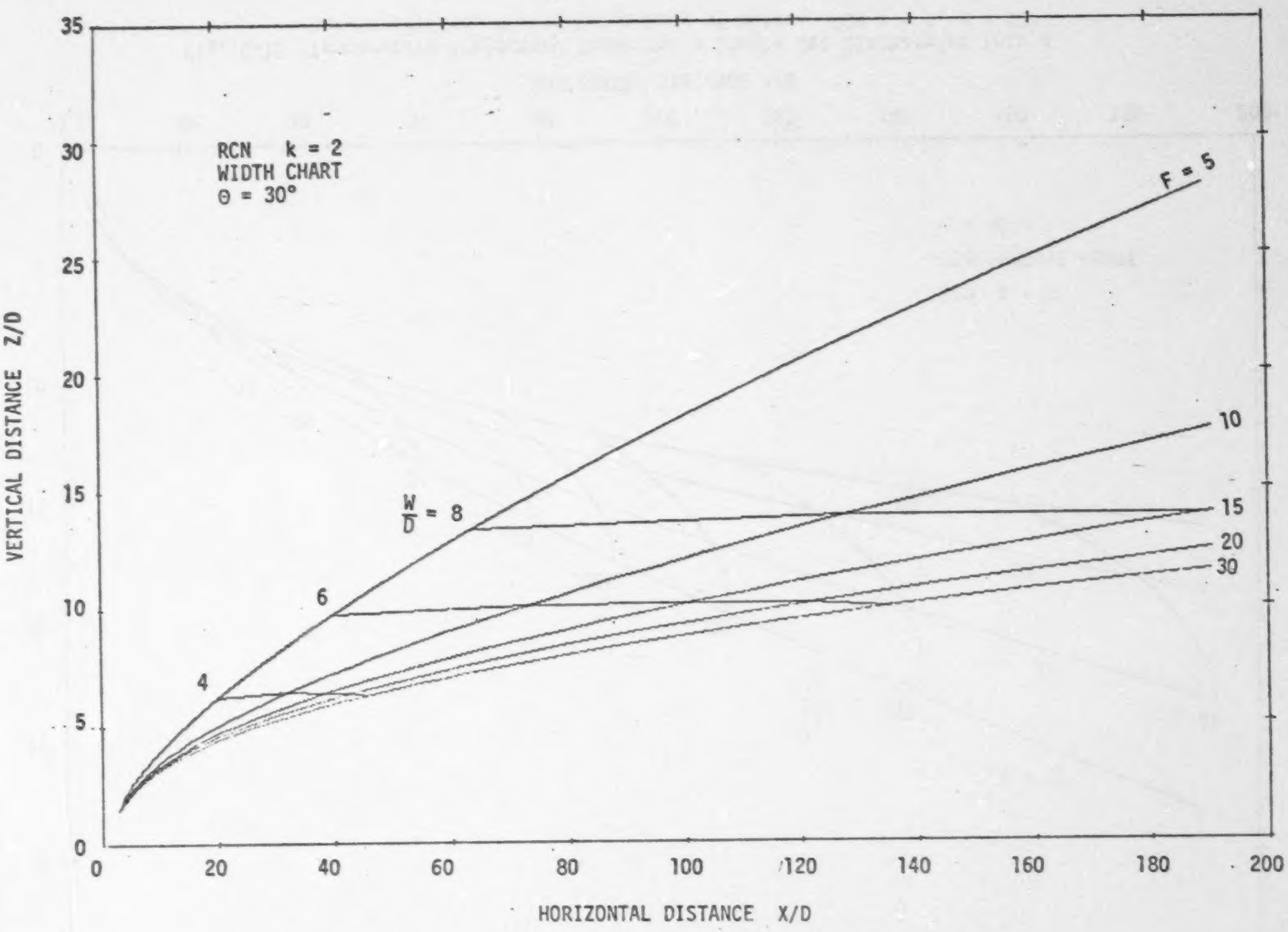

Fig. C-12 Width-Trajectory Chart for a Single Jet Discharging into a Non-Stratified, Moving Large Body of Water: RCN k = 2, Θ = 30°

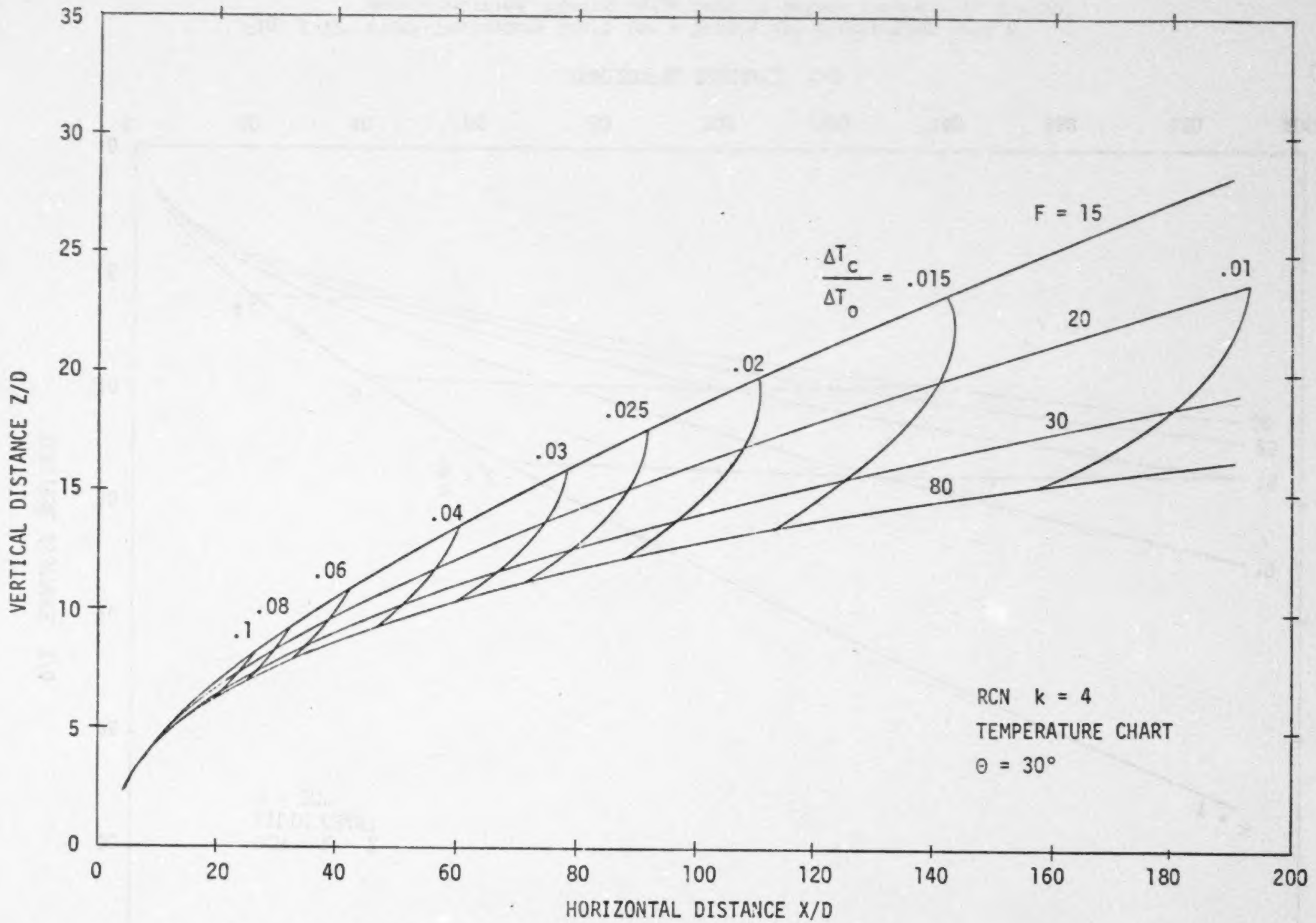

Fig. C-13 Temperature-Trajectory Chart for a Single Jet Discharging into a Non-Stratified, Moving Large Body of Water: RCN k = 4, Θ = 30°

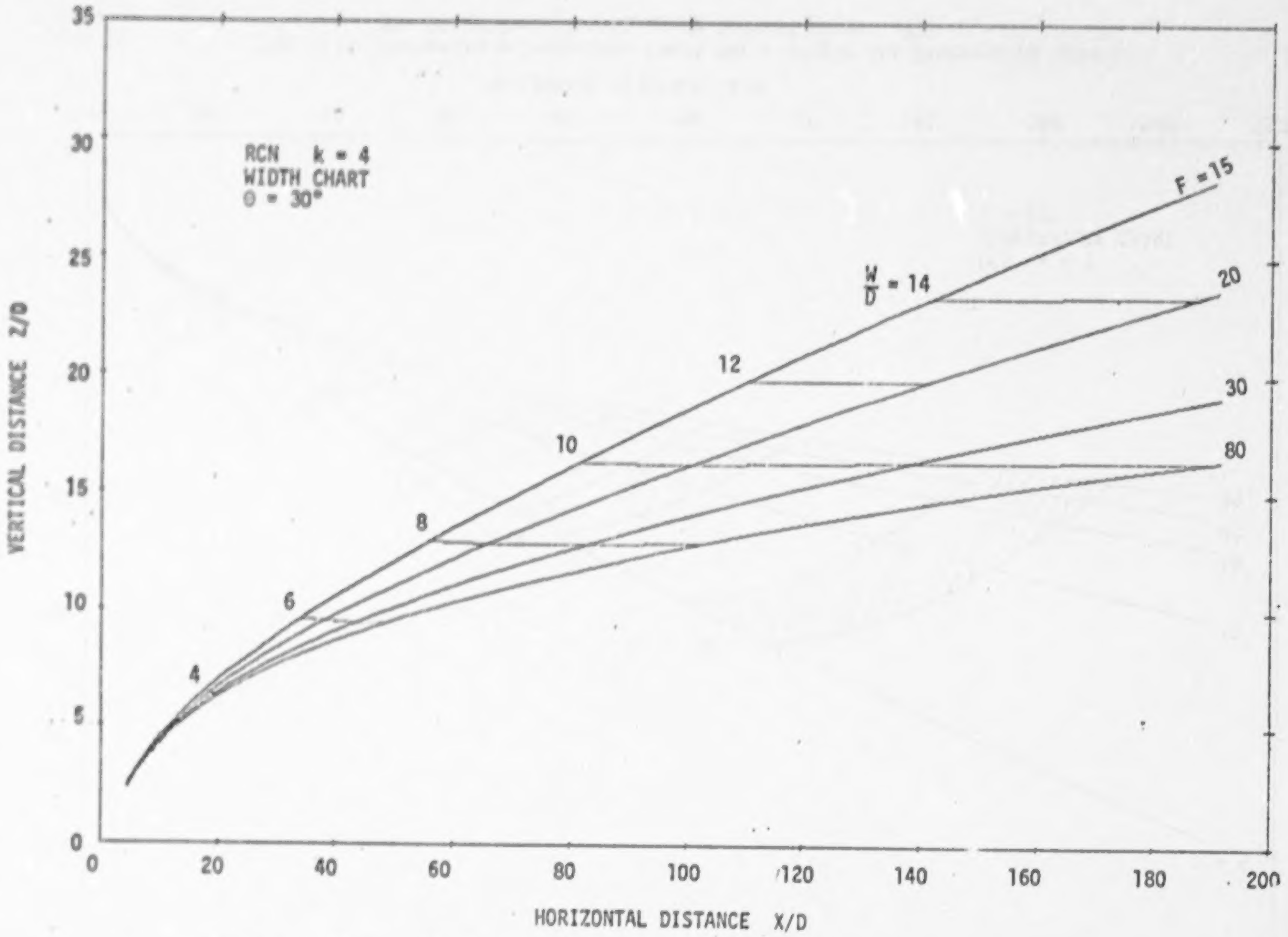

Fig. C-14 Width-Trajectory Chart for a Single Jet Discharging into a Non-Stratified, Moving Large Body of Water: RCN k = 4, Θ = 30°

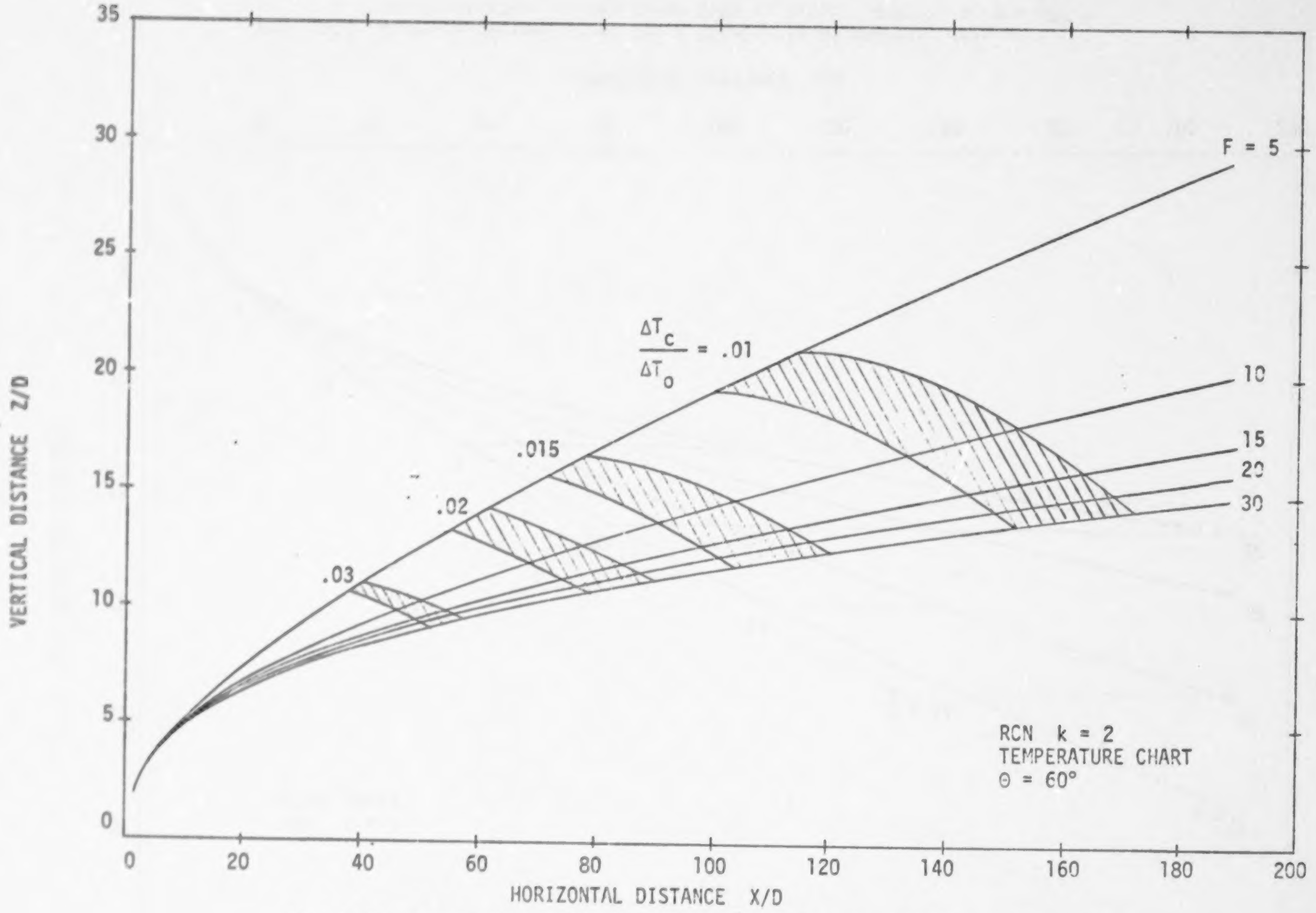

Fig. C-15 Temperature-Trajectory Chart for a Single Jet Discharging into a Non-Stratified, Moving Large Body of Water: RCN $k = 2$, $\Theta = 60°$

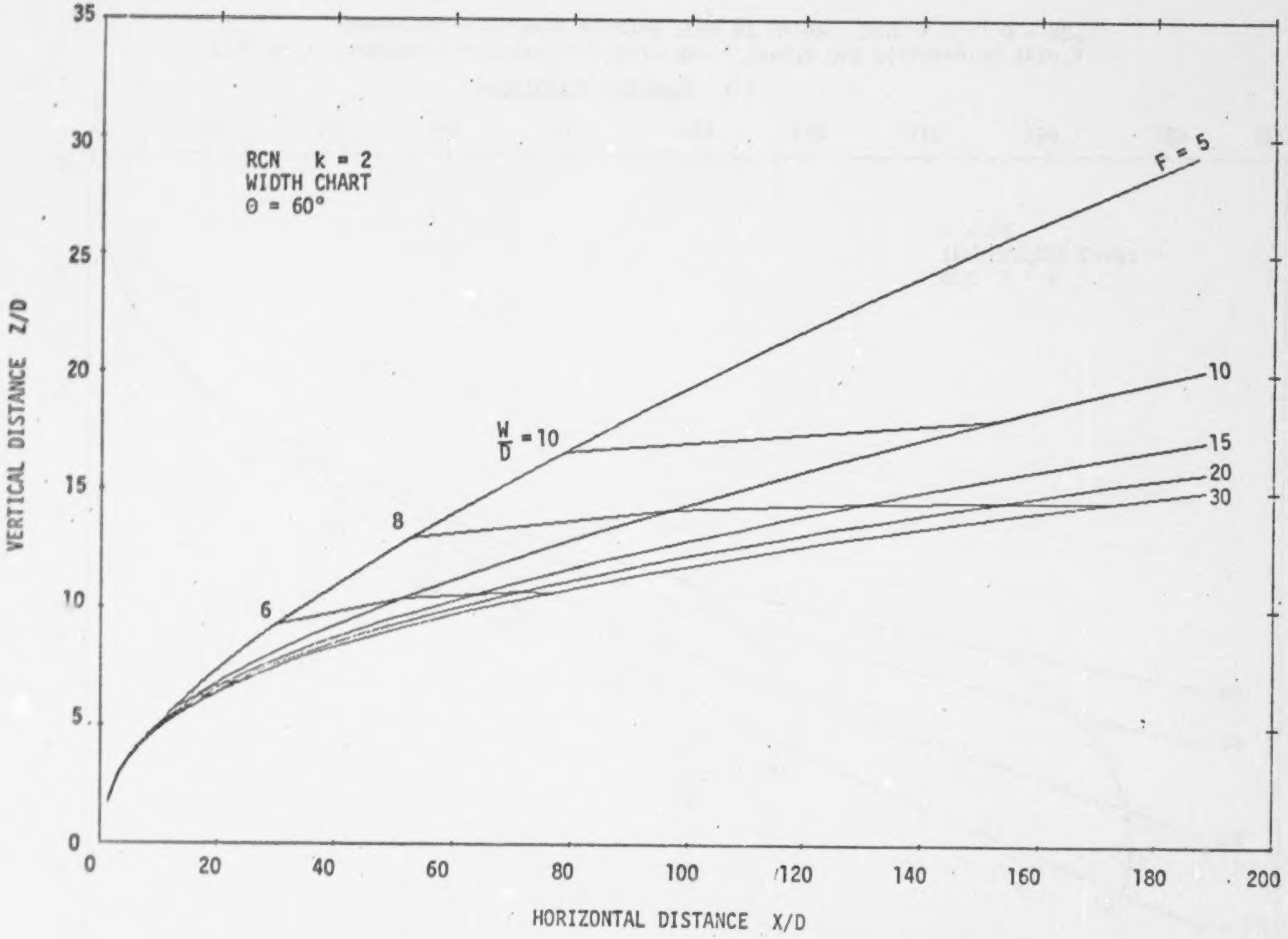

Fig. C-16 Width-Trajectory Chart for a Single Jet Discharging into a Non-Stratified, Moving Large Body of Water: RCN k = 2, Θ = 60°

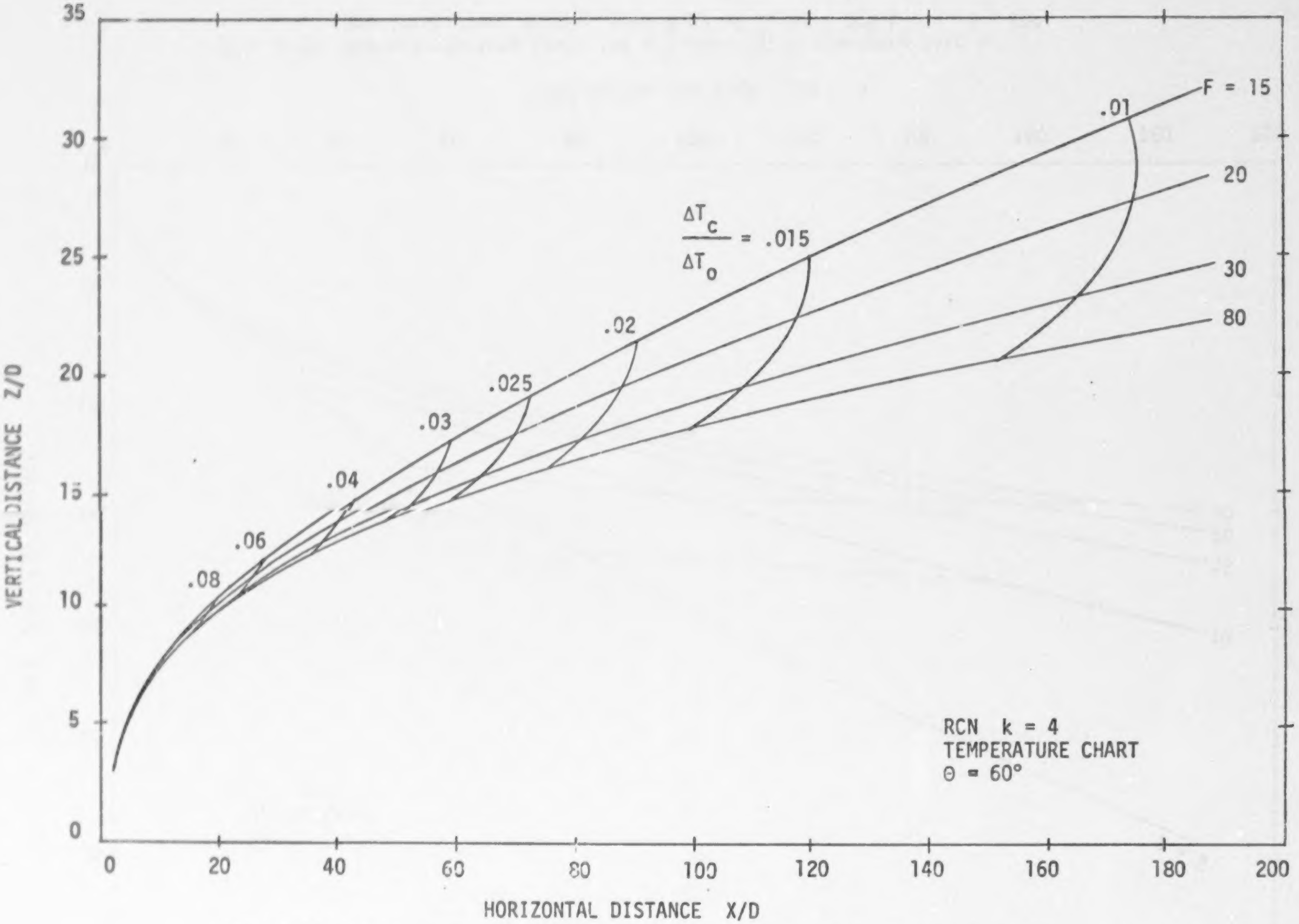

Fig. C-17 Temperature-Trajectory Chart for a Single Jet Discharging into a Non-Stratified, Moving Large Body of Water: RCN k = 4, Θ = 60°

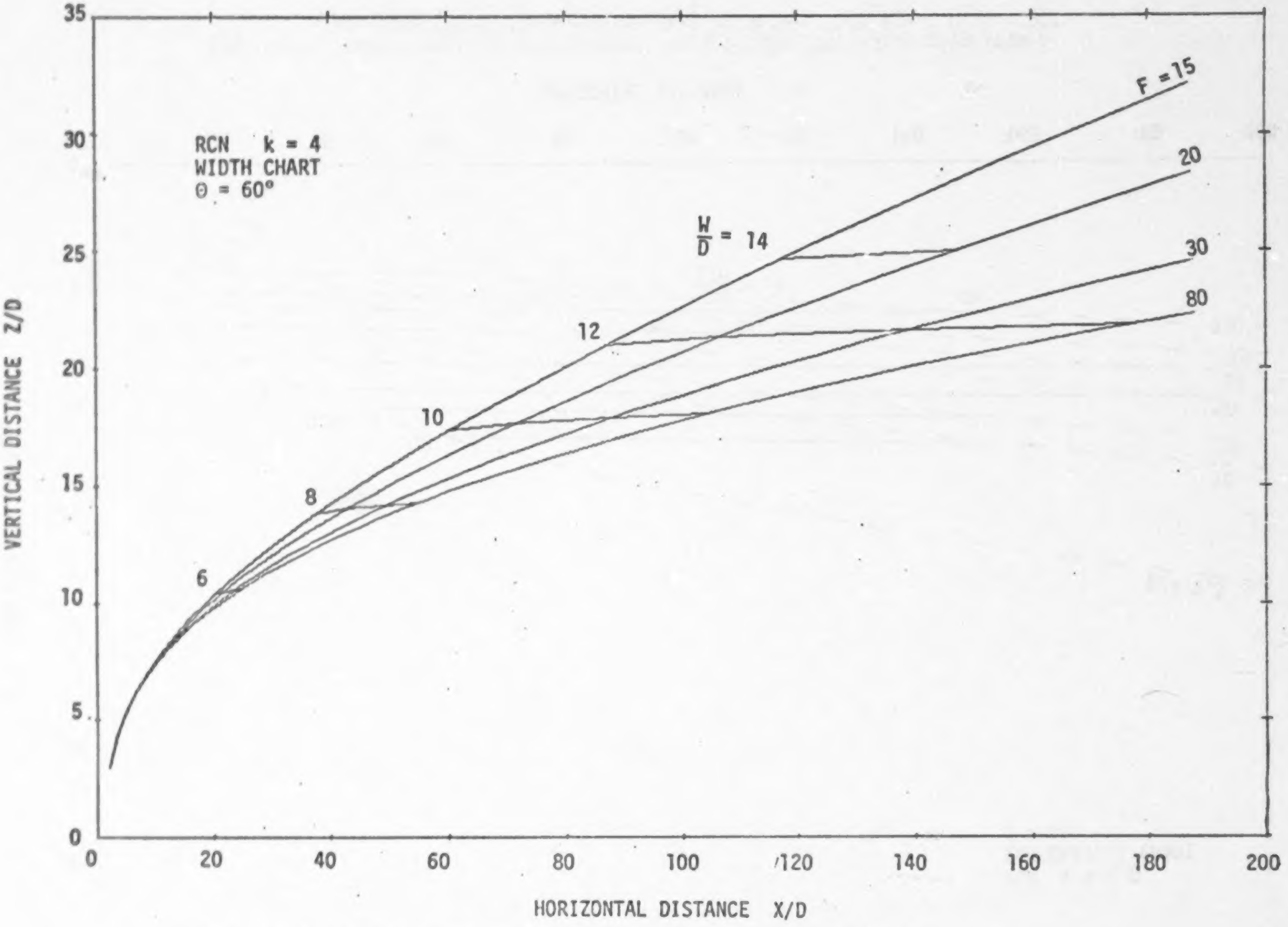

Fig. C-18 Width-Trajectory Chart for a Single Jet Discharging into a Non-Stratified, Moving Large Body of Water: RCN k = 4, Θ = 60°

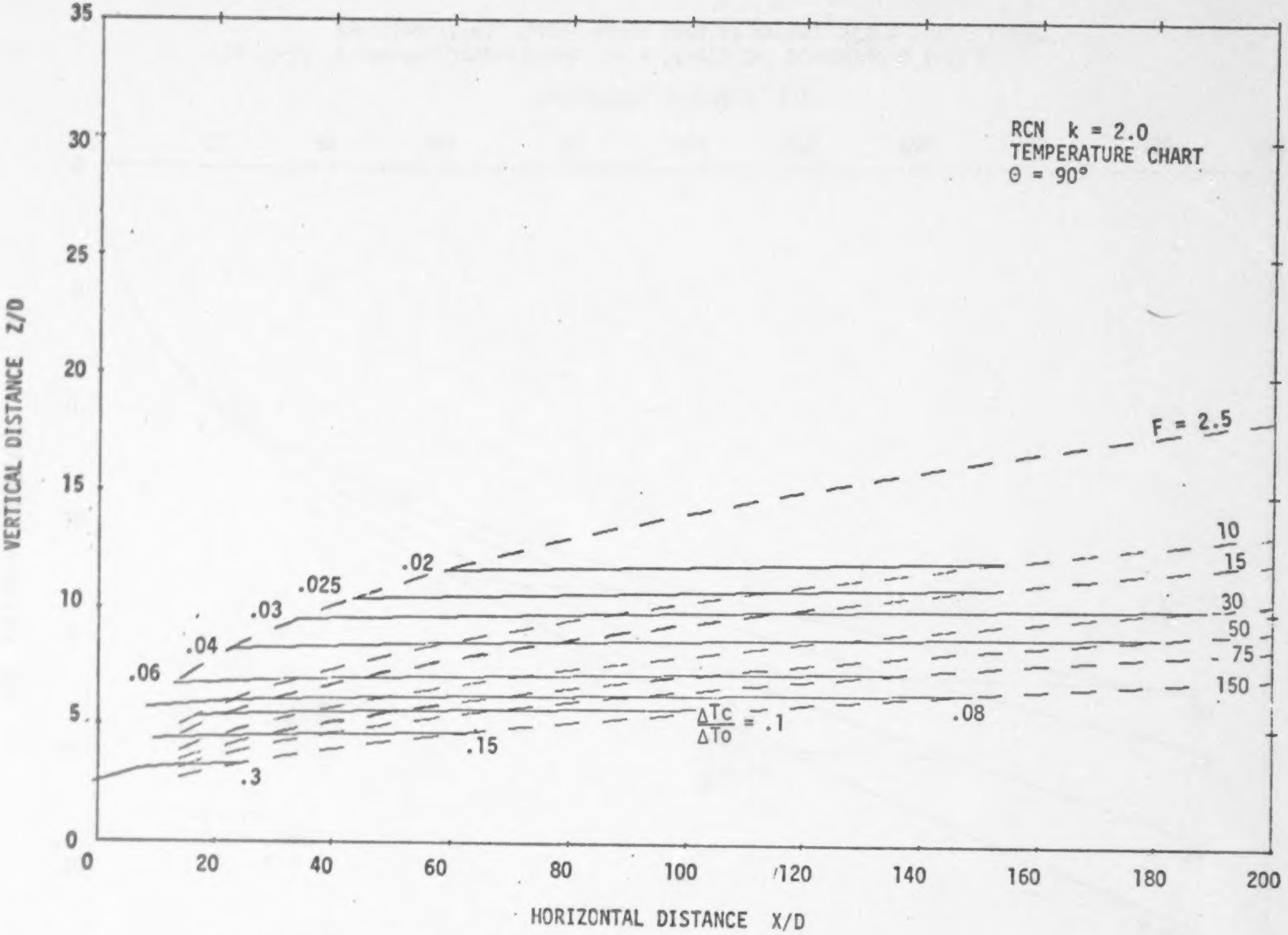

Fig. C-19 Temperature-Trajectory Chart for a Single Jet Discharging into a Non-Stratified, Moving Large Body of Water: RCN k = 2.0, Θ = 90°

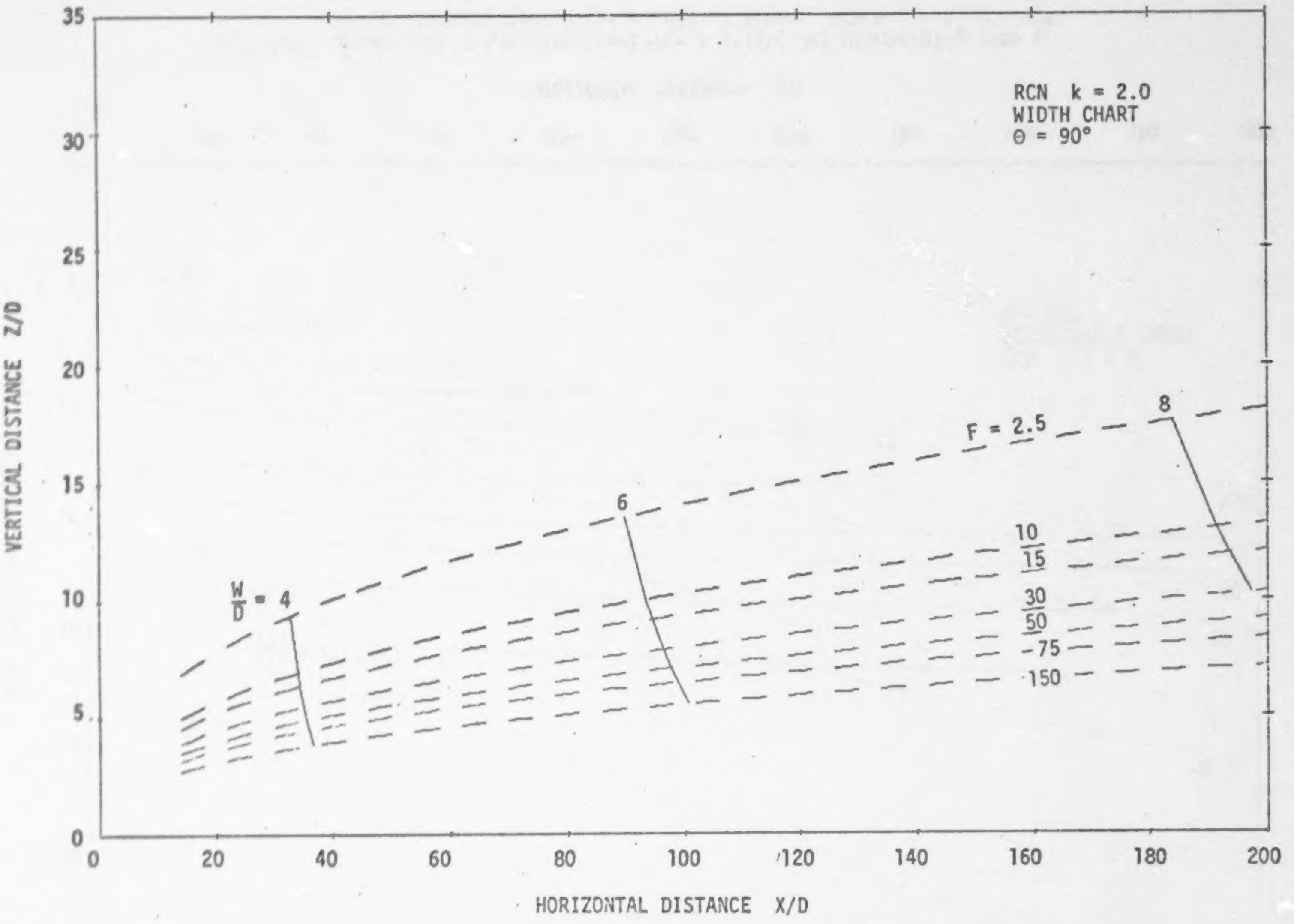

Fig. C-20 Width-Trajectory Chart for a Single Jet Discharging into a Non-Stratified, Moving Large Body of Water: RCN k = 2.0, Θ = 90°

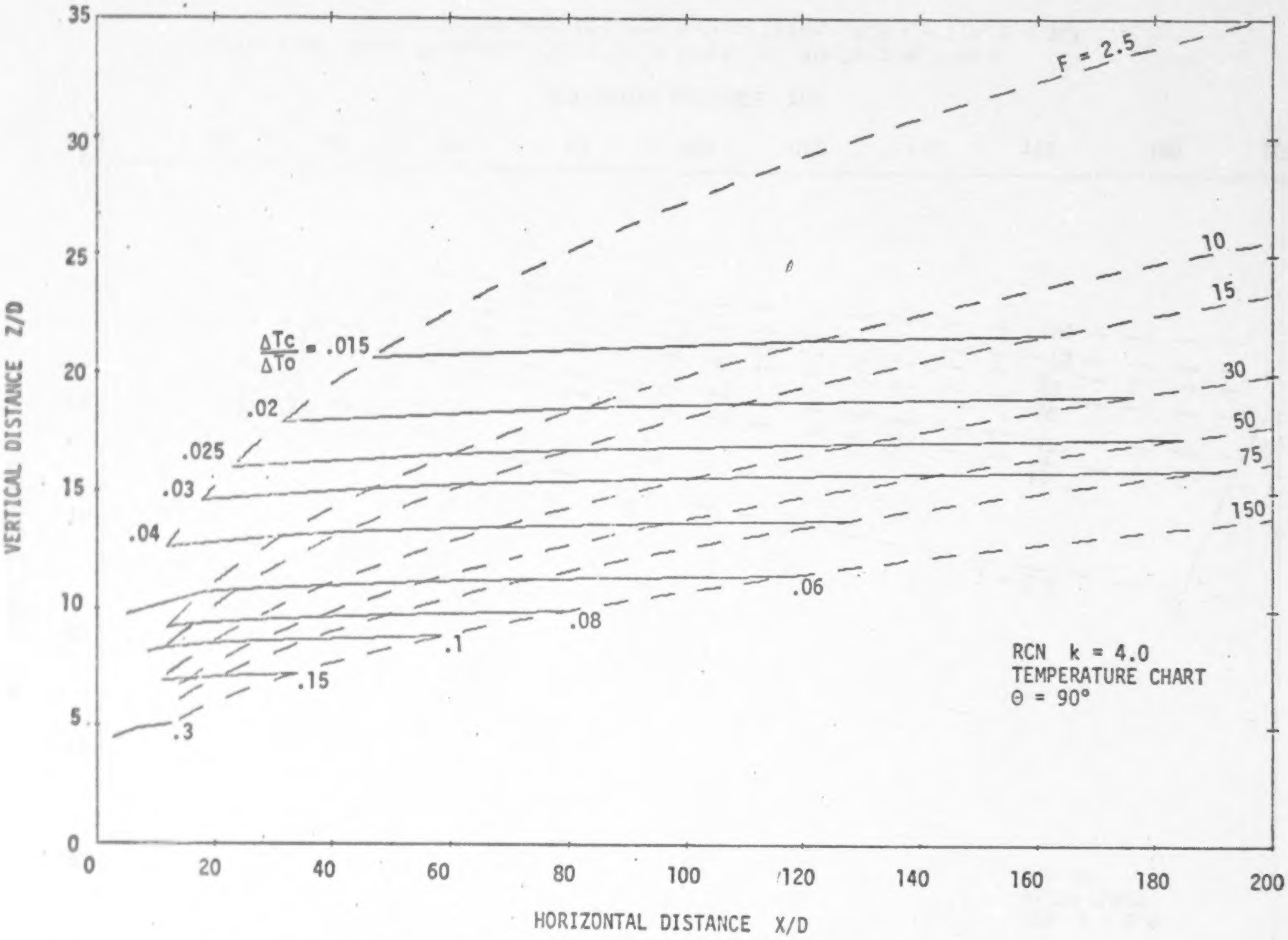

Fig. C-21 Temperature-Trajectory Chart for a Single Jet Discharging into a Non-Stratified, Moving Large Body of Water: RCN k = 4.0, Θ = 90°

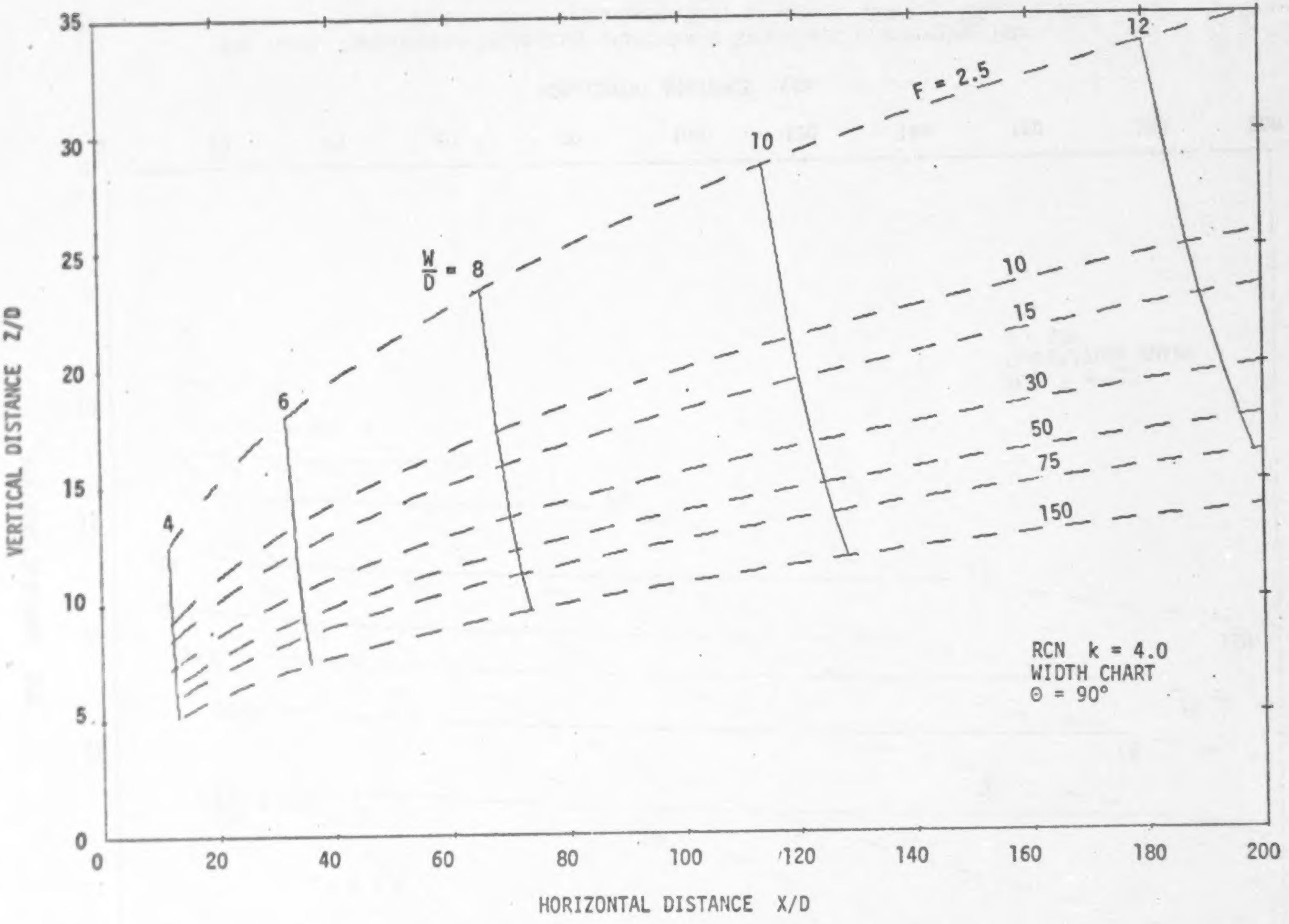

Fig. C-22 Width-Trajectory Chart for a Single Jet Discharging into a Non-Stratified, Moving Large Body of Water: RCN k = 4.0, Θ = 90°

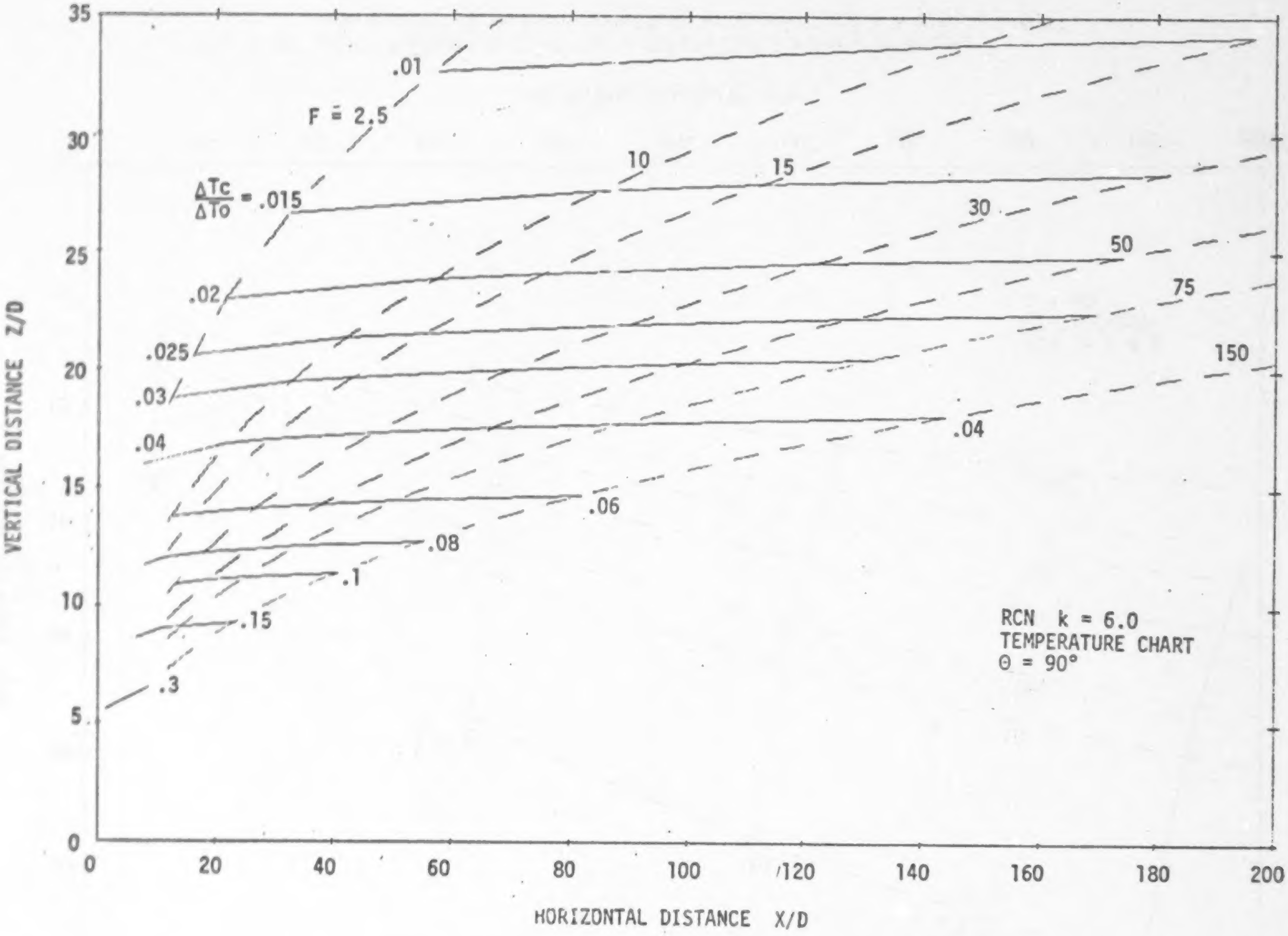

Fig. C-23 Temperature-Trajectory Chart for a Single Jet Discharging into a Non-Stratified, Moving Large Body of Water: RCN k = 6.0, Θ = 90°

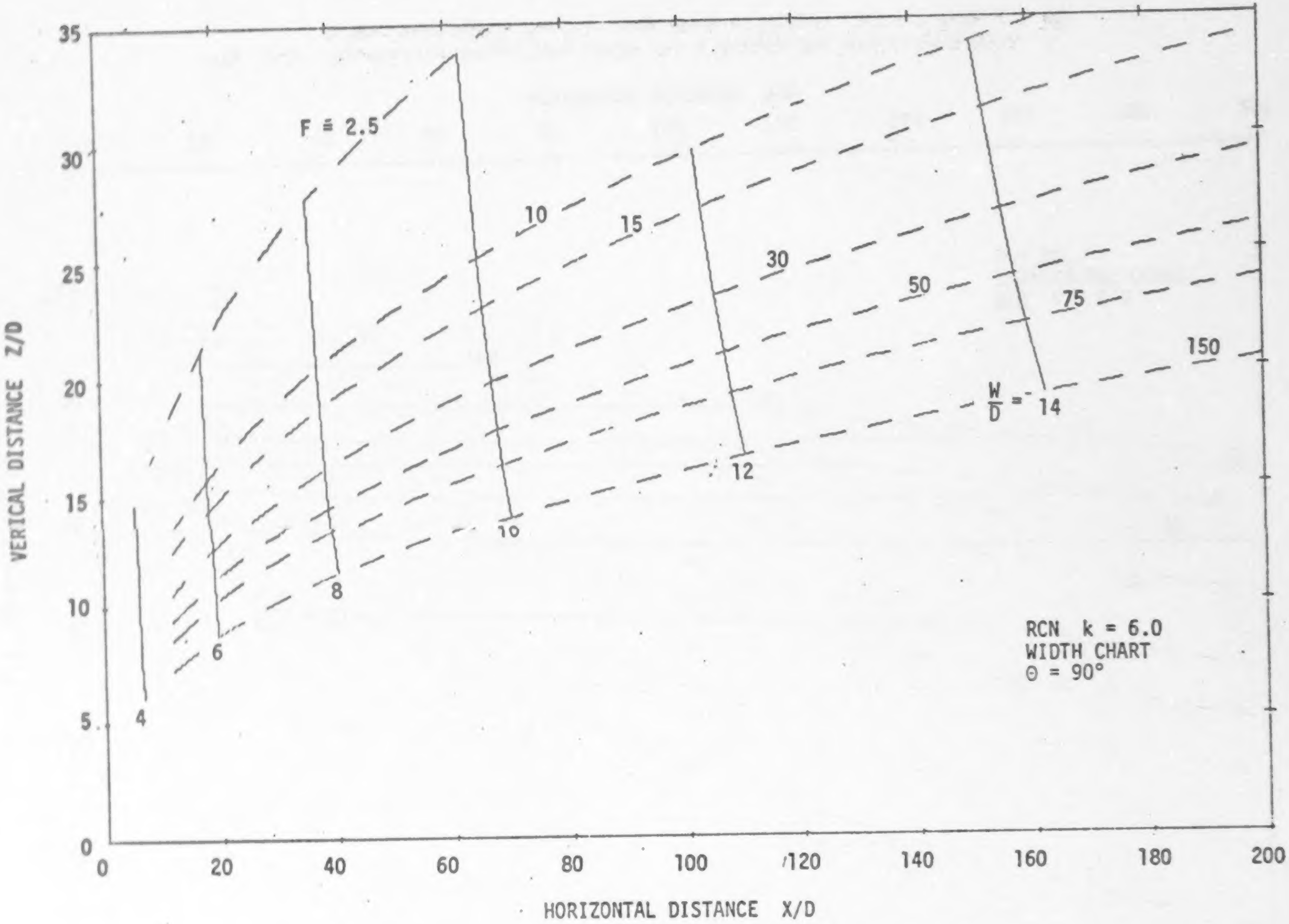

Fig. C-24 Width-Trajectory Chart for a Single Jet Discharging into a Non-Stratified, Moving Large Body of Water: RCN k = 6.0, Θ = 90°

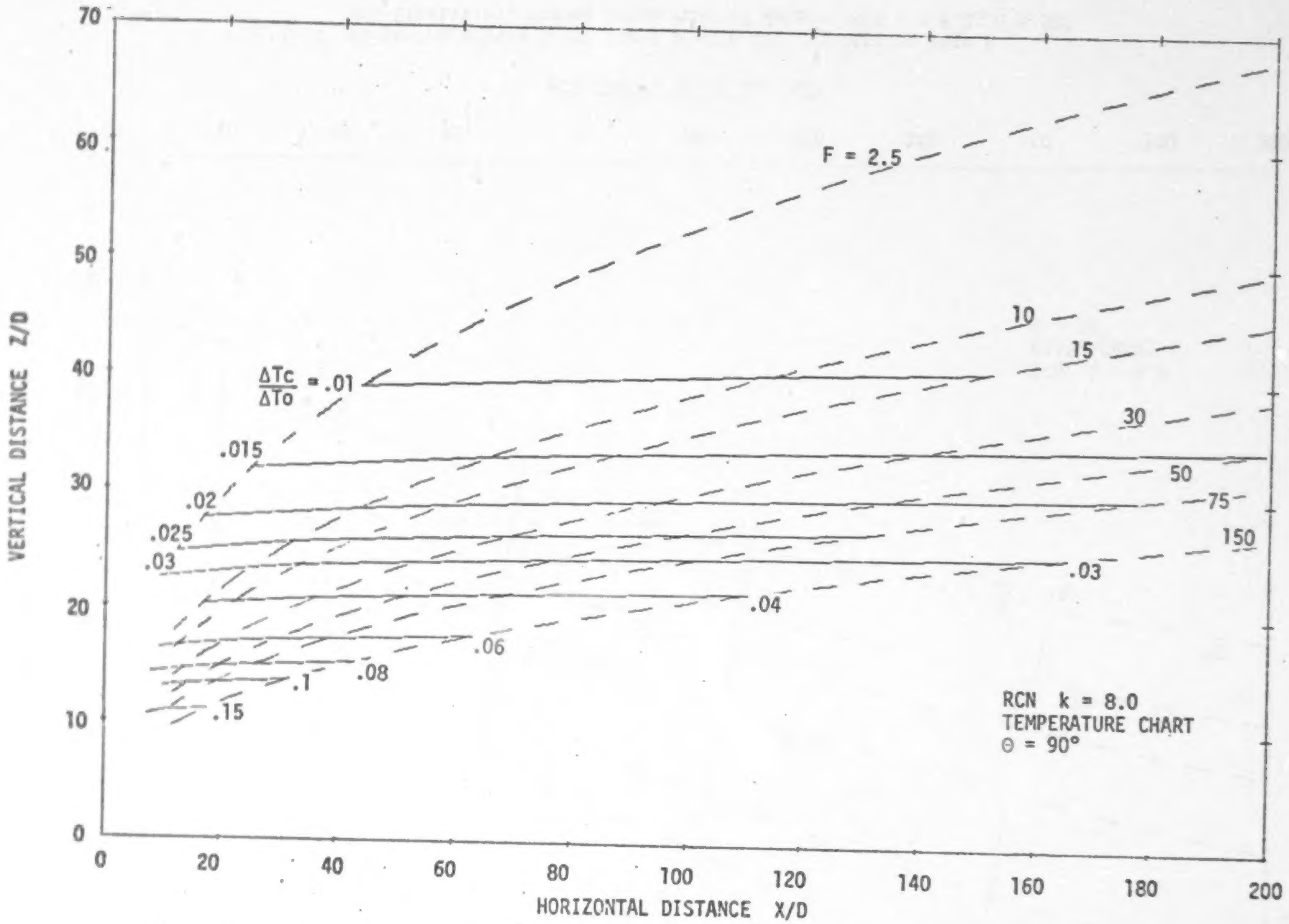

Fig. C-25 Temperature-Trajectory Chart for a Single Jet Discharging into a Non-Stratified, Moving Large Body of Water: RCN k = 8.0, Θ = 90°

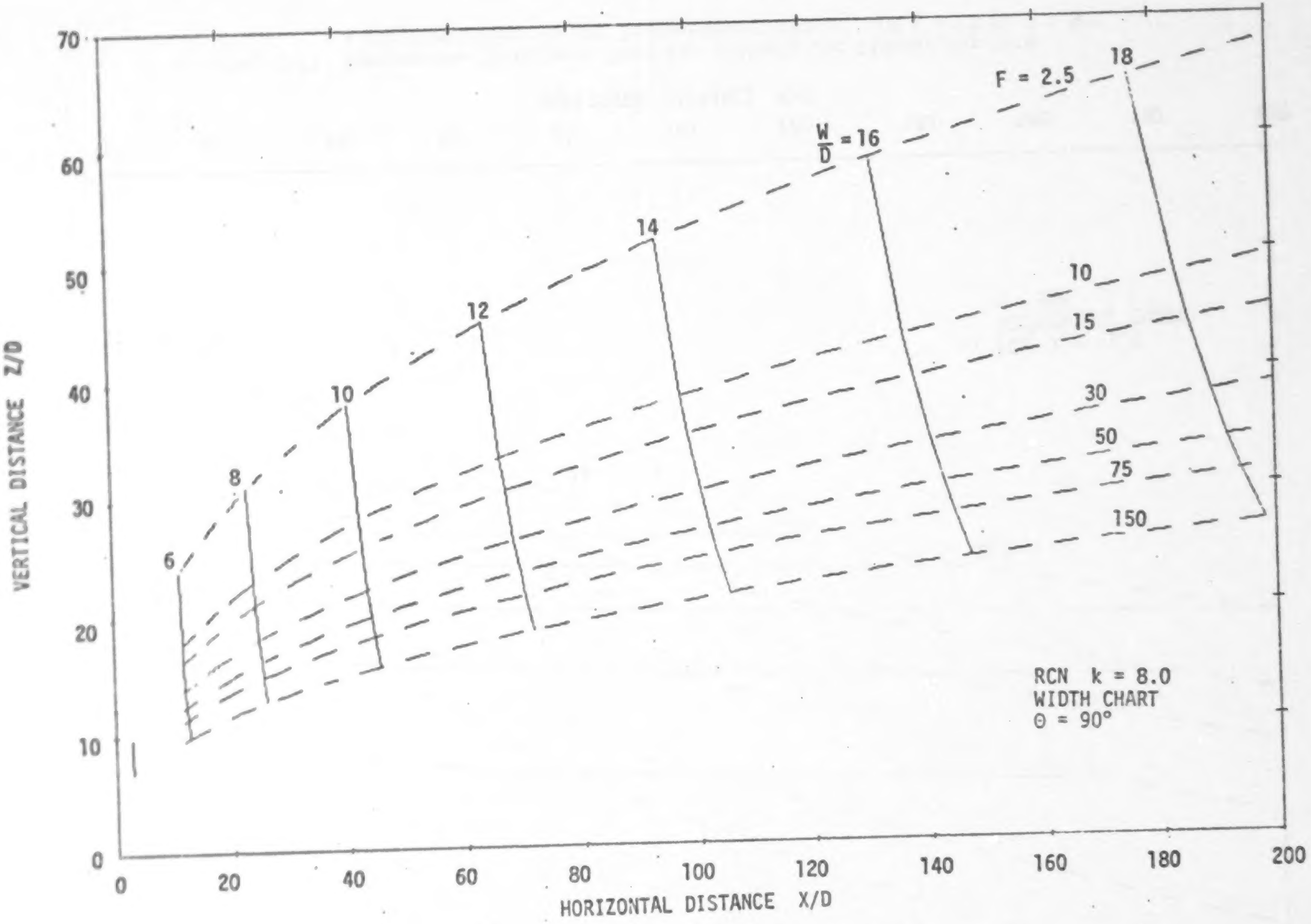

Fig. C-26 Width-Trajectory Chart for a Single Jet Discharging into a Non-Stratified, Moving Large Body of Water: RCN k = 8.0, Θ = 90°

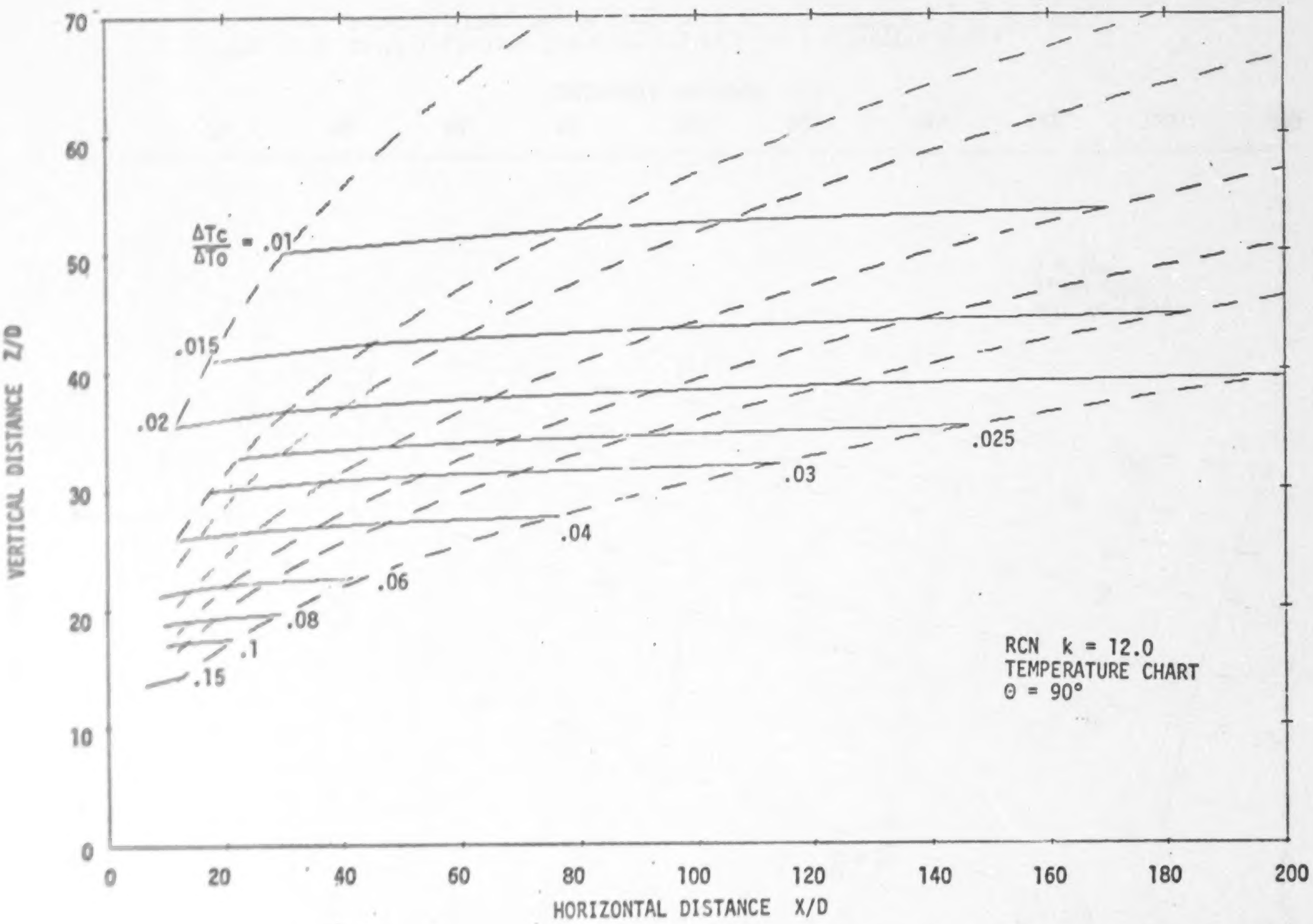

Fig. C-27 Temperature-Trajectory Chart for a Single Jet Discharging into a Non-Stratified, Moving Large Body of Water: RCN k = 12.0, Θ = 90°

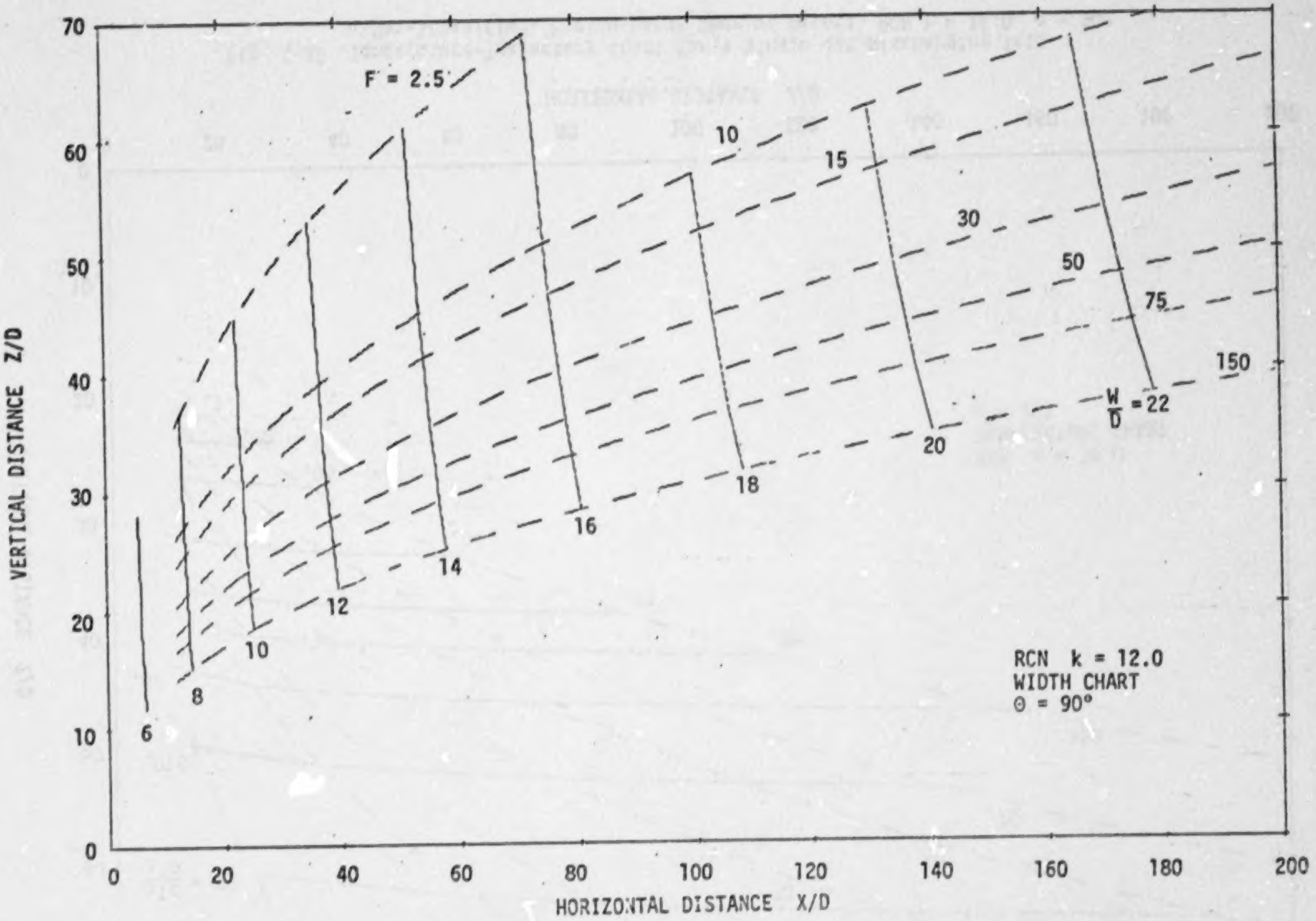

Fig. C-28 Width-Trajectory Chart for a Single Jet Discharging into a Non-Stratified, Moving Large Body of Water: RCN k = 12.0, Θ = 90°

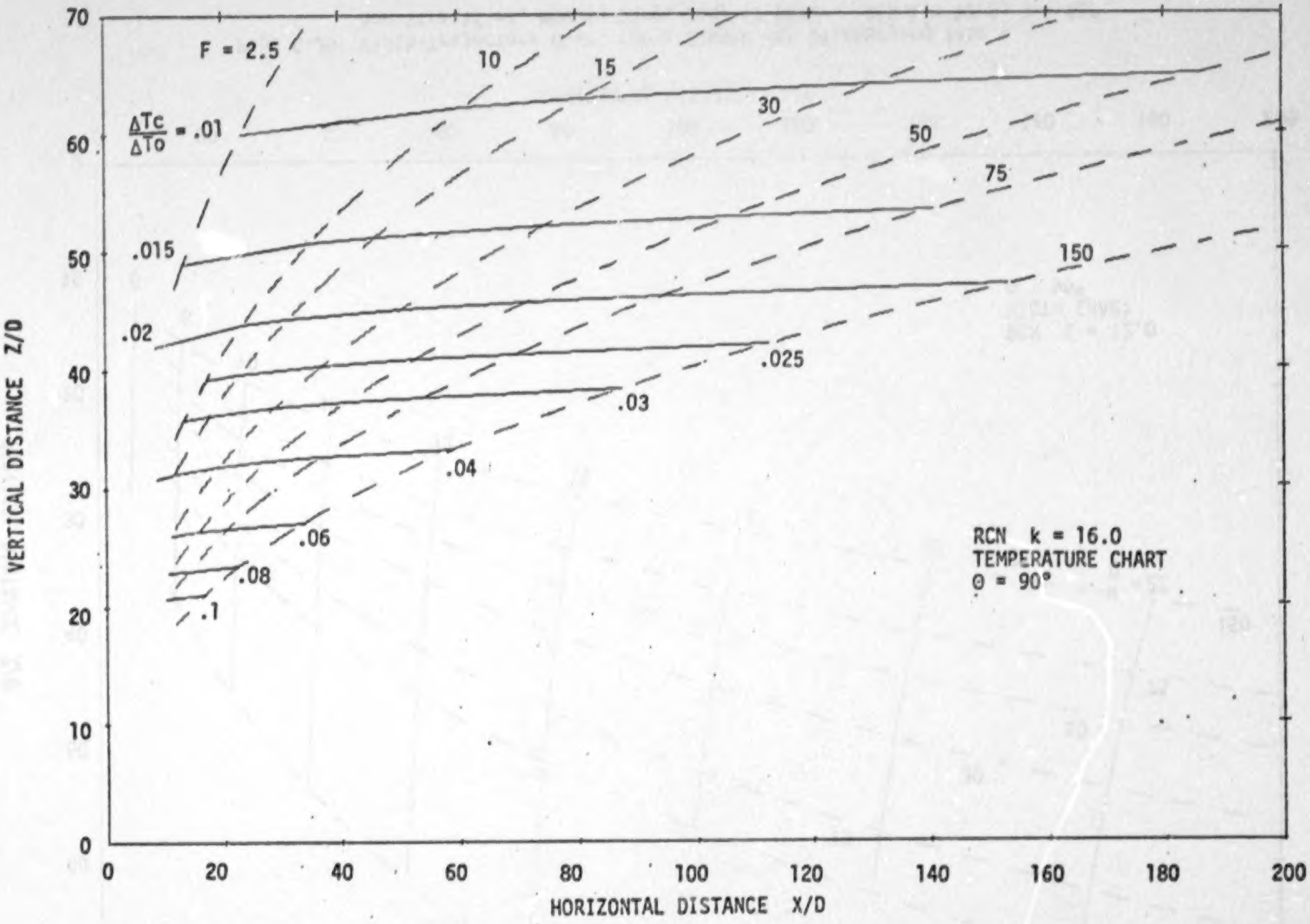

Fig. C-29 Temperature-Trajectory Chart for a Single Jet Discharging into a Non-Stratified, Moving Large Body of Water: RCN k = 16.0, Θ = 90°

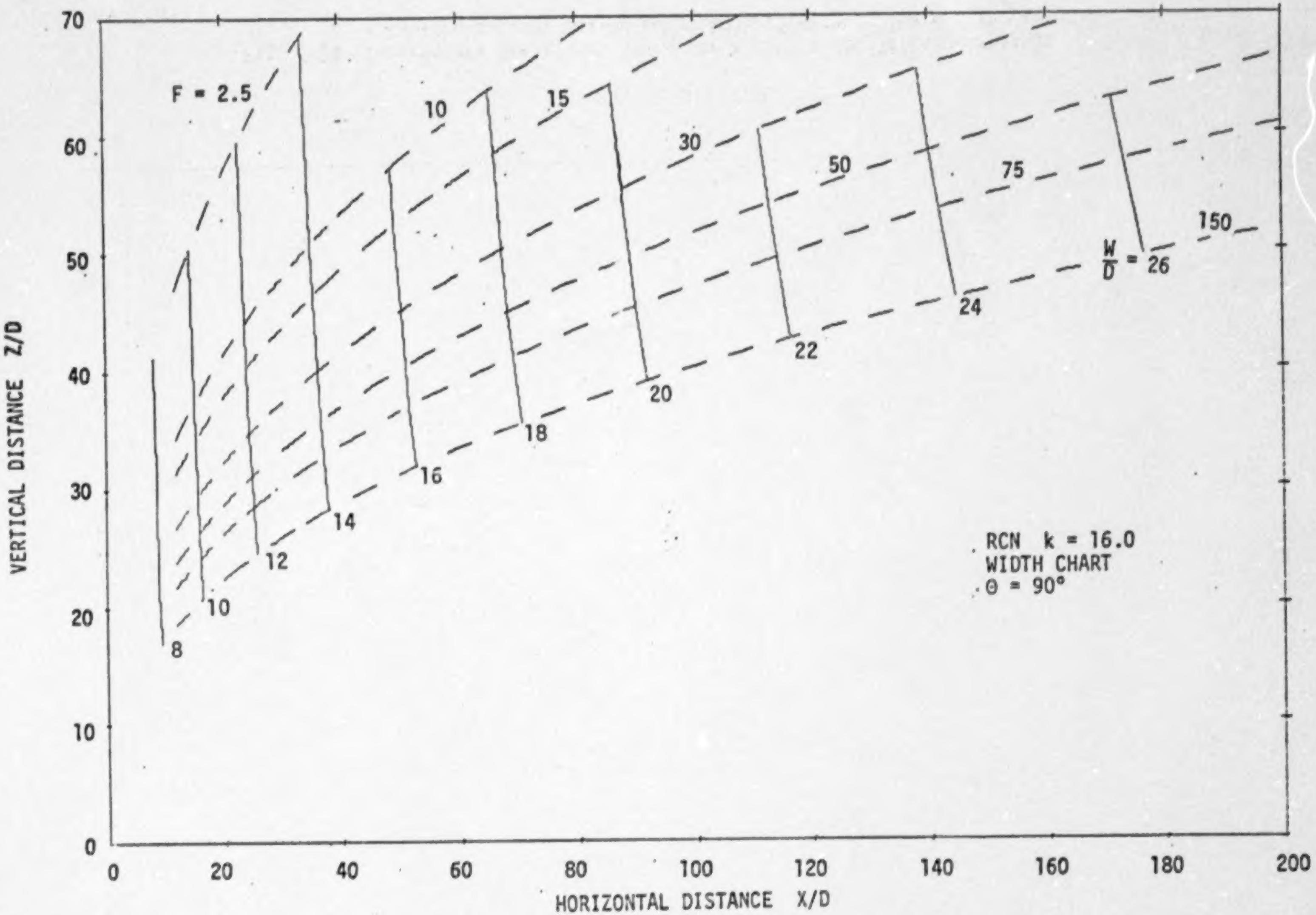

Fig. C-30 Width-Trajectory Chart for a Single Jet Discharging into a Non-Stratified, Moving Large Body of Water: RCN k = 16.0, Θ = 90°

APPENDIX D

Nomograms for Discharge into Moving, Stratified Water (RCS)

TABLE IV

Figure Numbers Corresponding to Plume Behavior for Diffuser Discharging into Moving and Stratified Ambient Water

S_t	k = 2		k = 4	
	F = 10	F = 30	F = 30	F = 75
100	D-1,2	D-3,4	D-5,6	D-7,8
500	D-9,10	D-11,12	D-13,14	D-15,16

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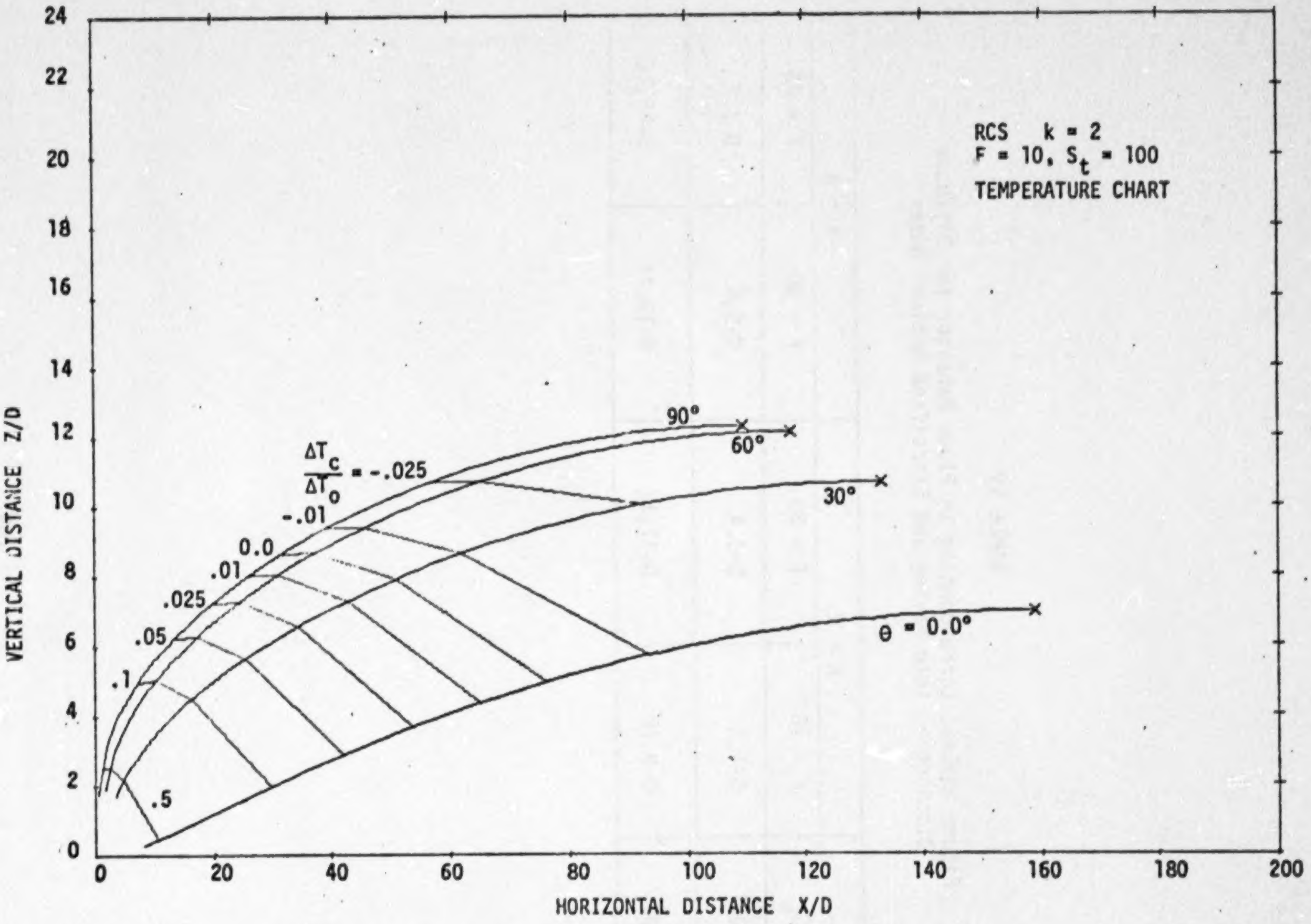

Fig. D-1 Temperature-Trajectory for a Single Jet Discharging into a Stratified, Moving Large Body of Water: RCS k = 2, S_t = 100, F = 10

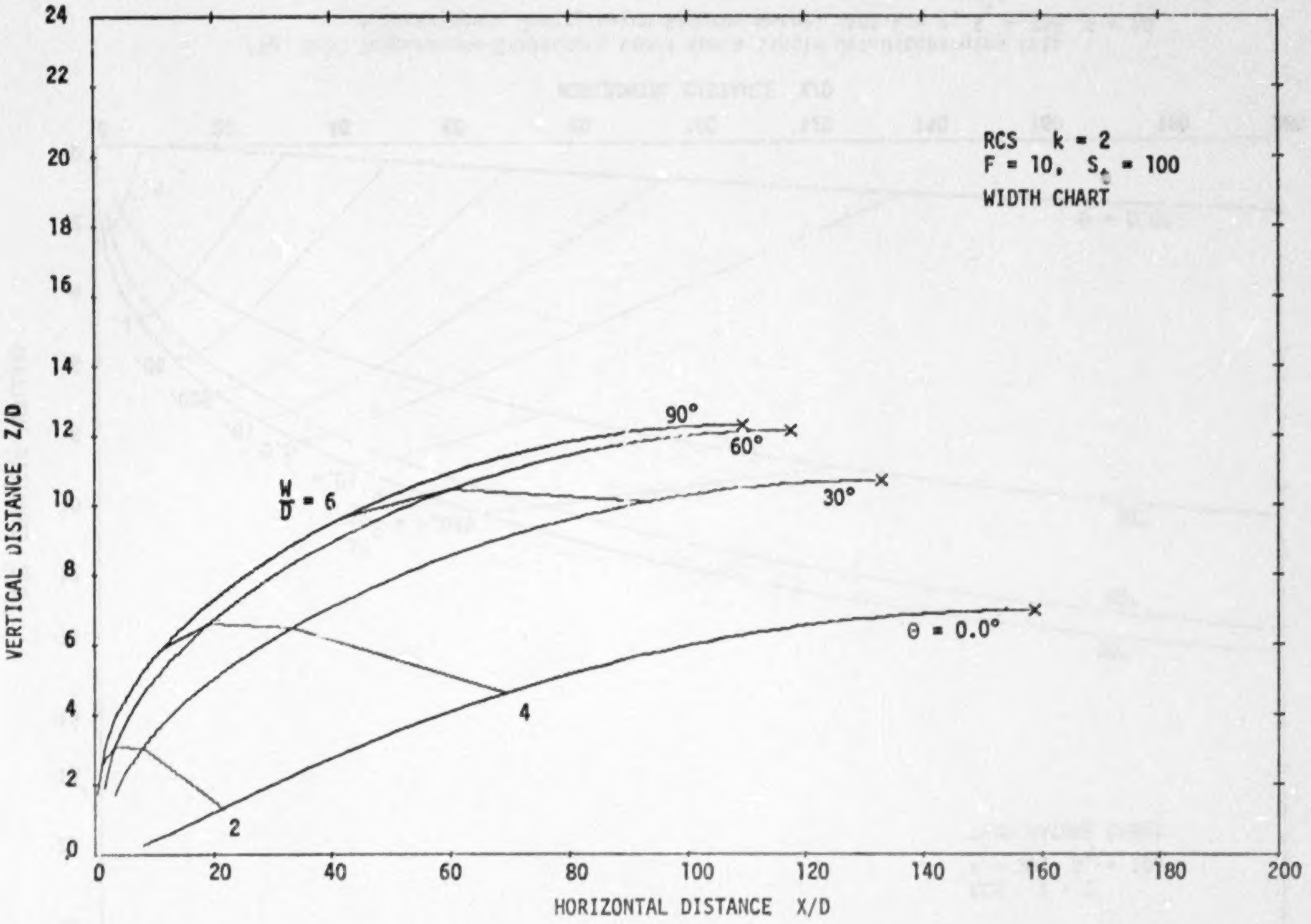

Fig. D-2 Width-Trajectory Chart for a Single Jet Discharging into a Stratified, Moving Large Body of Water: RCS k = 2, S_t = 100, F = 10

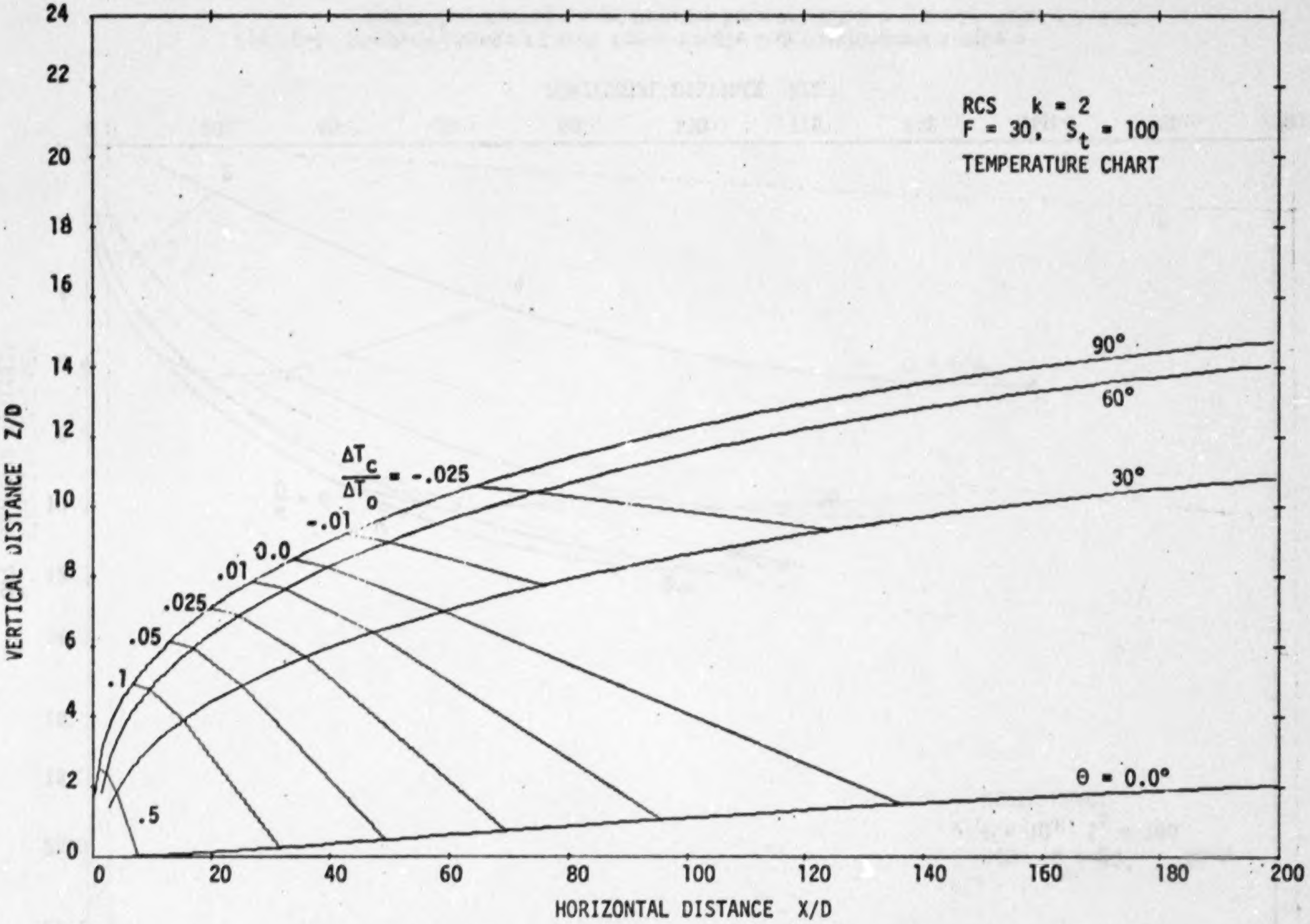

Fig. D-3 Temperature-Trajectory Chart for a Single Jet Discharging into a Stratified, Moving Large Body of Water: RCS k = 2, S_t = 100, F = 30

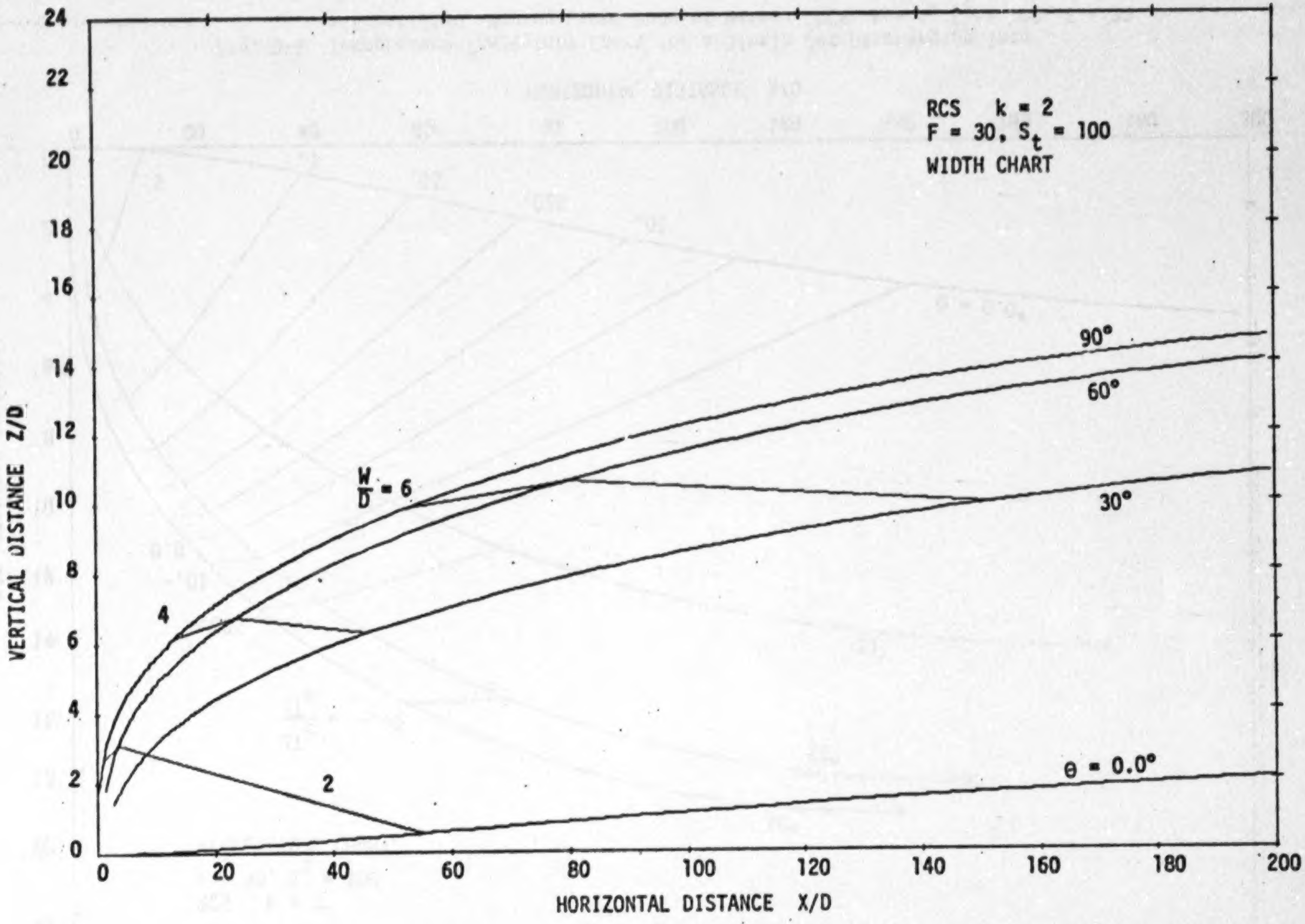

Fig. D-4 Width-Trajectory Chart for a Single Jet Discharging into a Stratified, Moving Large Body of Water: RCS k = 2, S_t = 100, F = 30

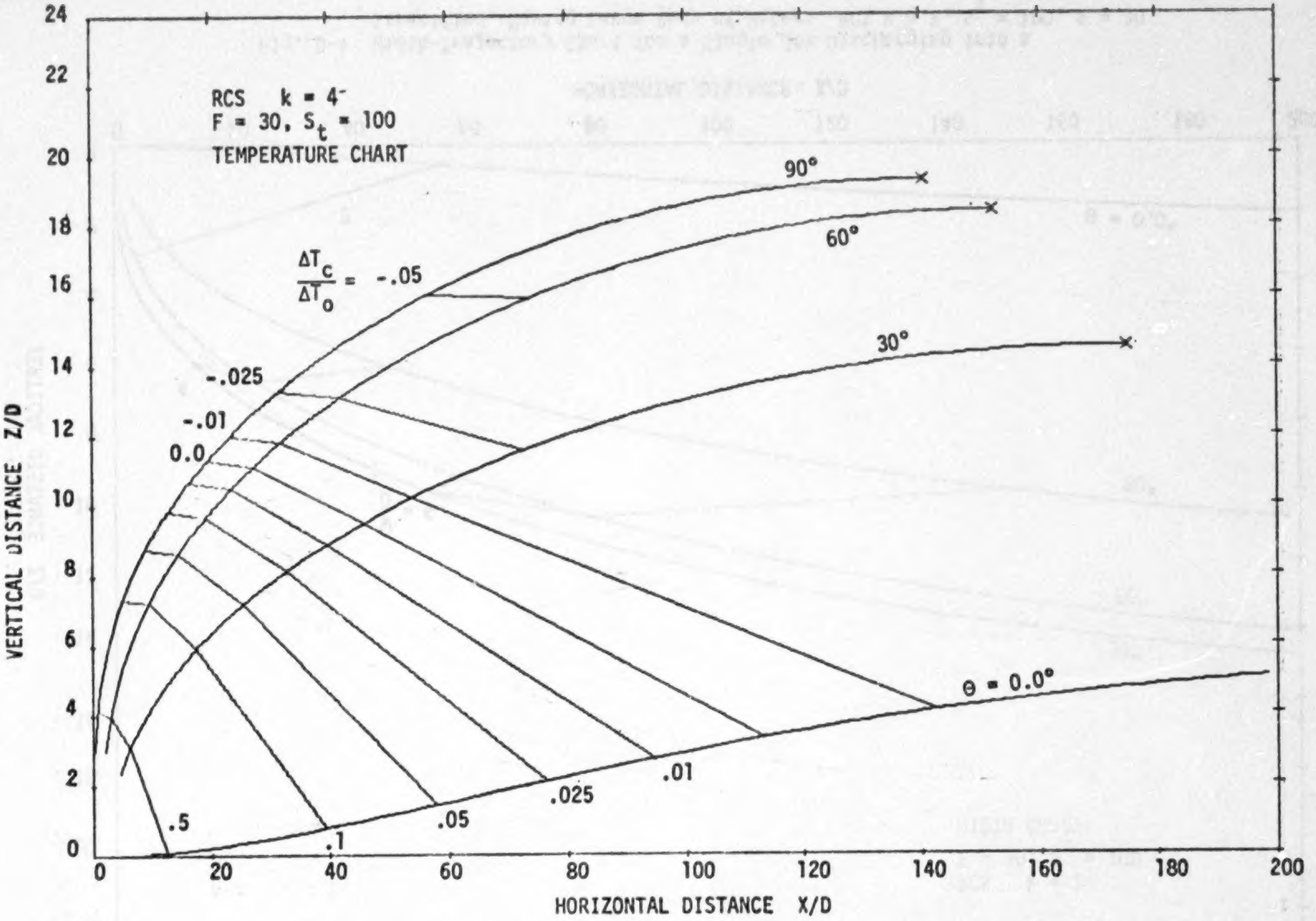

Fig. D-5 Temperature-Trajectory Chart for a Single Jet Discharging into a Stratified, Moving Large Body of Water: RCS k = 4, S_t = 100, F = 30

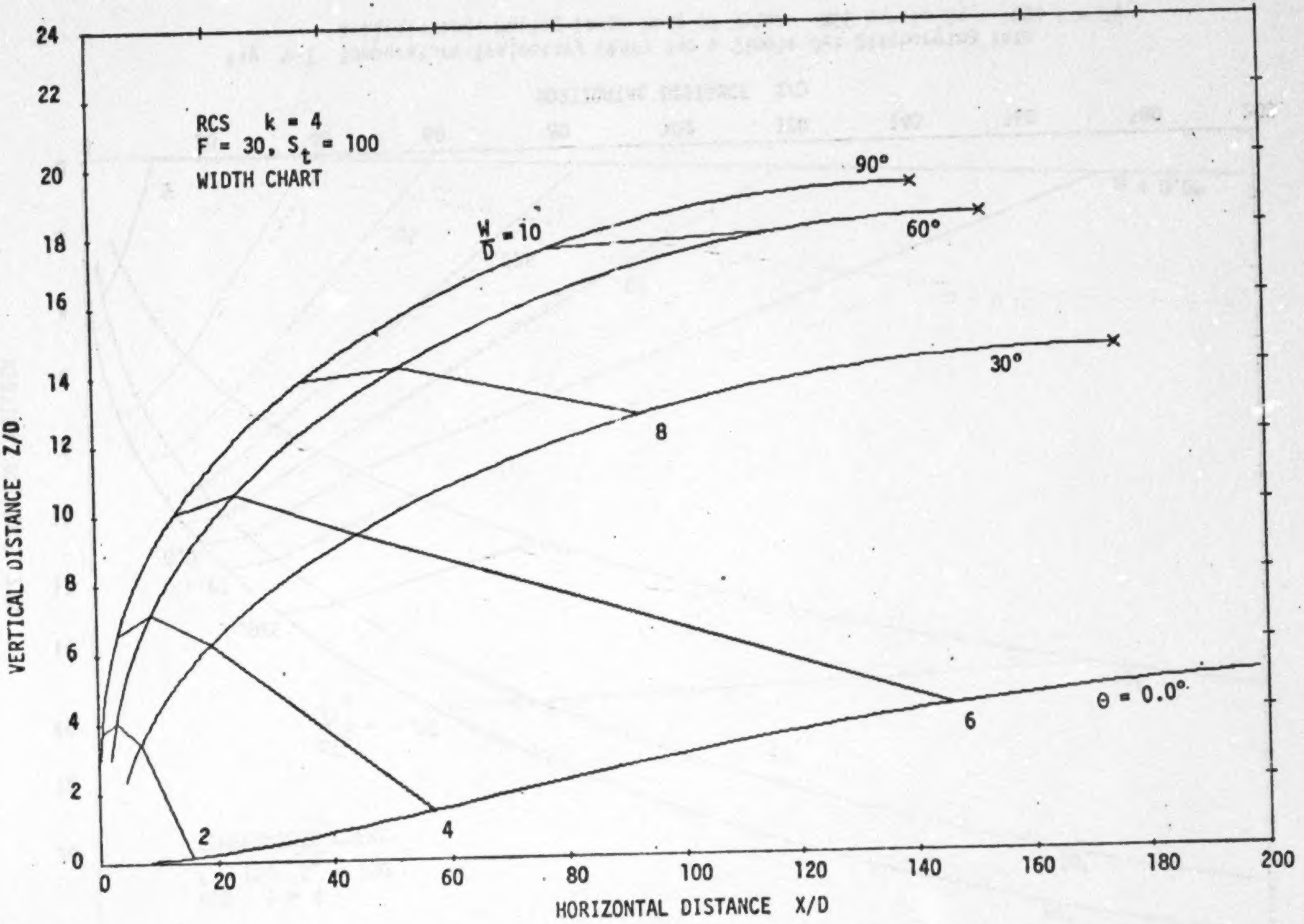

Fig. D-6 Width-Trajectory Chart for a Single Jet Discharging into a Stratified, Moving Large Body of Water: RCS k = 4, S_t = 100, F = 30

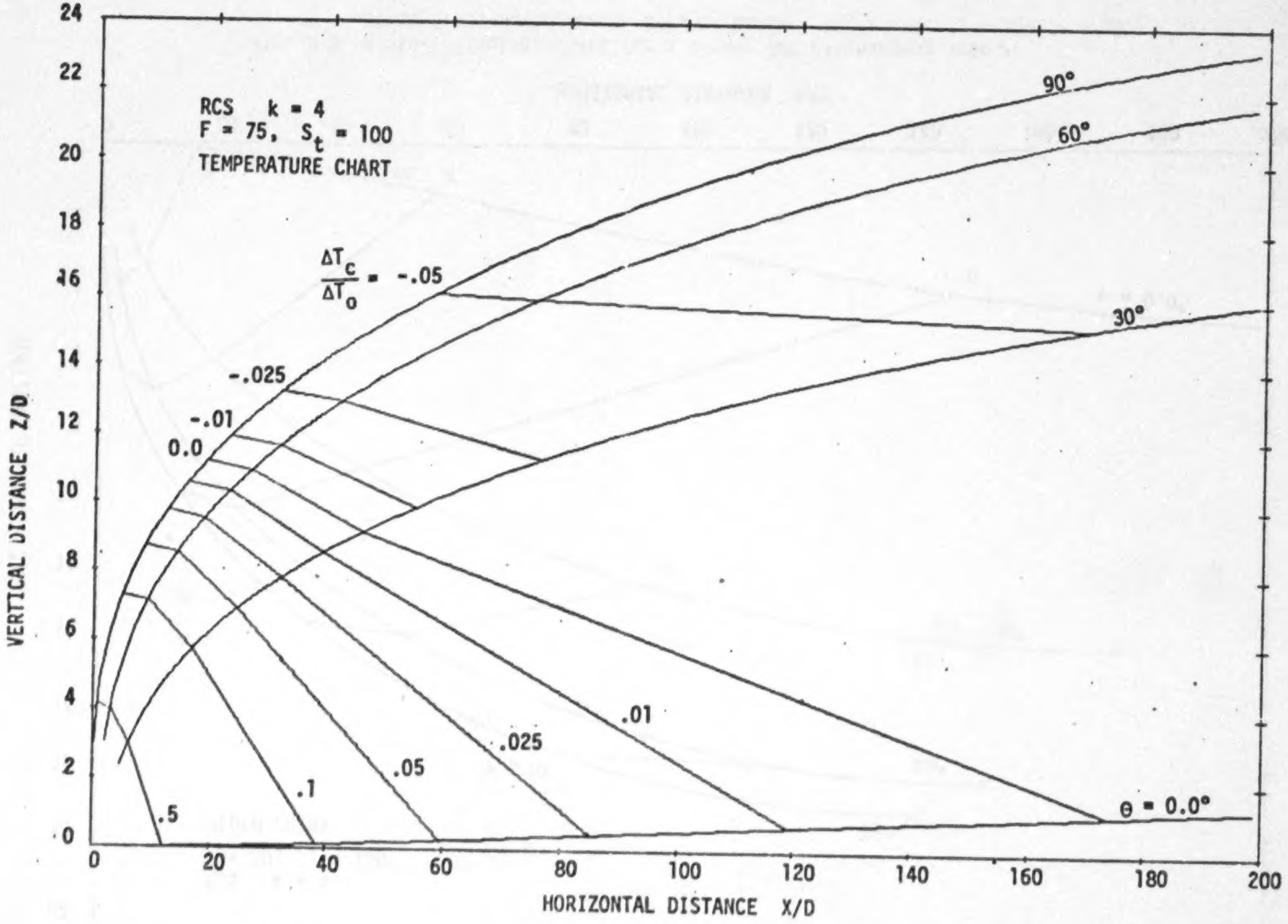

Fig. D-7 Temperature-Trajectory Chart for a Single Jet Discharging into a Stratified, Moving Large Body of Water: RCS k = 4, S_t = 100, F = 75

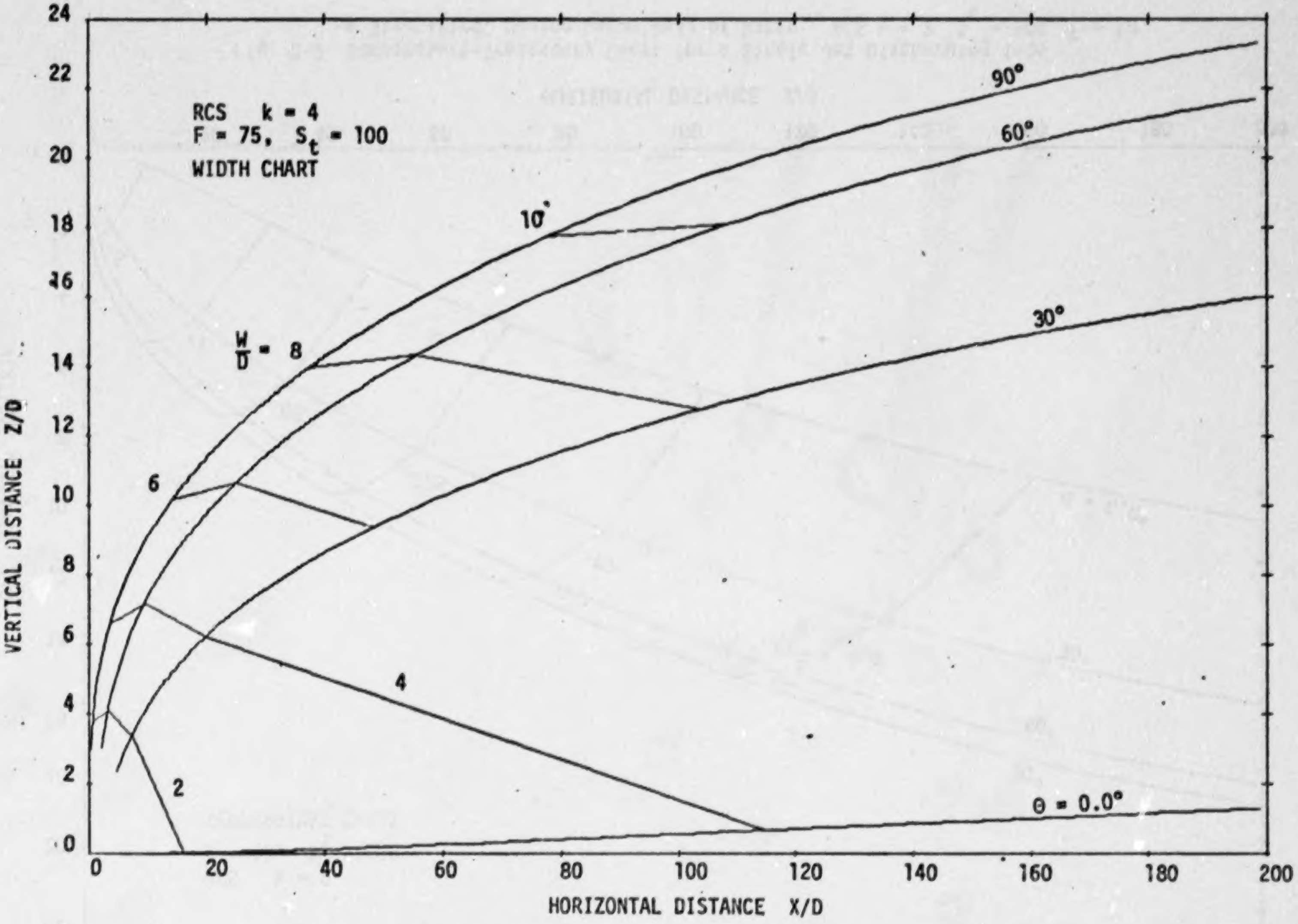

Fig. D-8 Width-Trajectory Chart for a Single Jet Discharging into a Stratified, Moving Large Body of Water: RCS k = 4, S_t = 100, F = 75

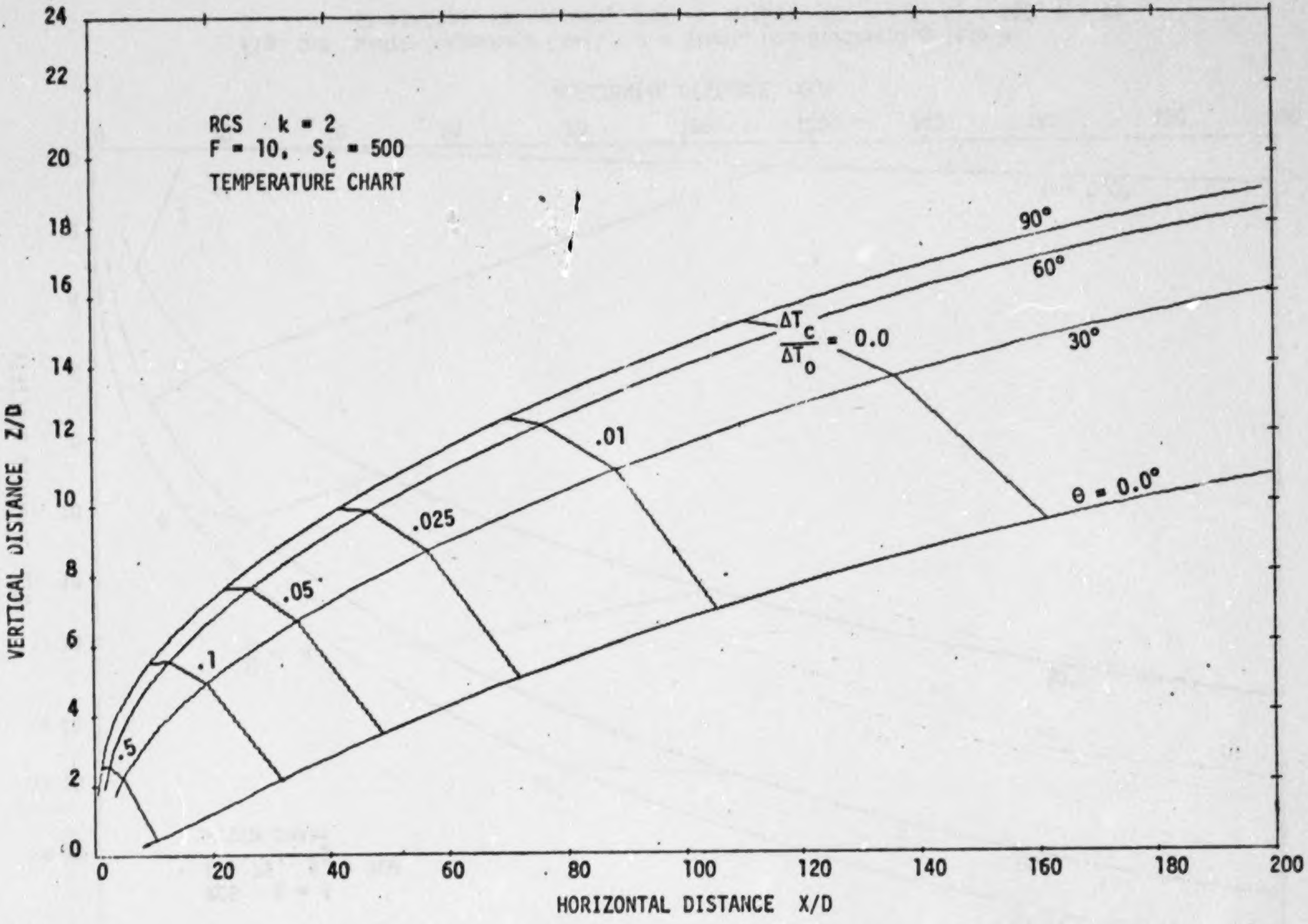

Fig. D-9 Temperature-Trajectory Chart for a Single Jet Discharging into a Stratified, Moving Large Body of Water: RCS k = 2, S_t = 500, F = 10

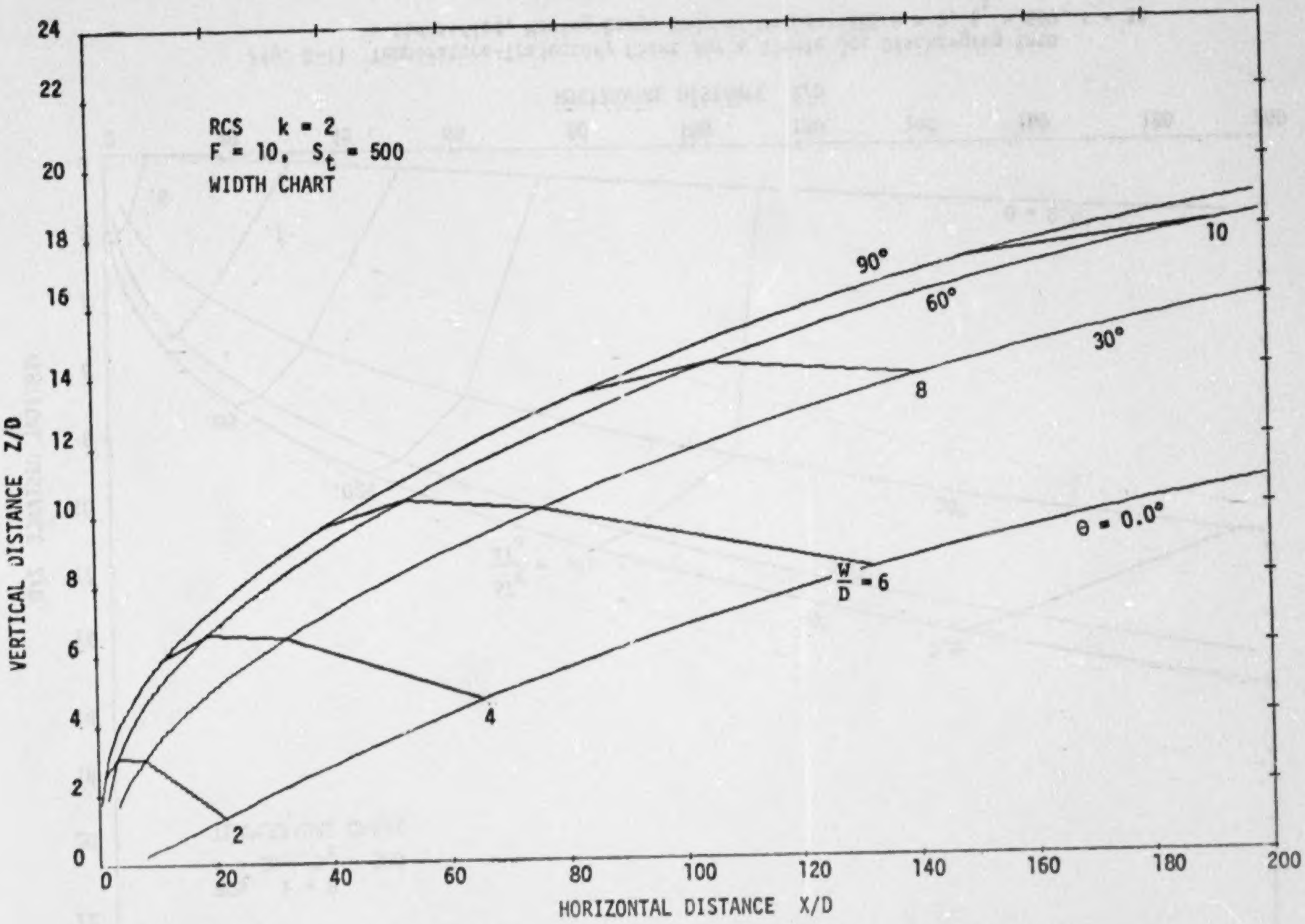

Fig. D-10 Width-Trajectory Chart for a Single Jet Discharging into a Stratified, Moving Large Body of Water: RCS k = 2, S_t = 500, F = 10

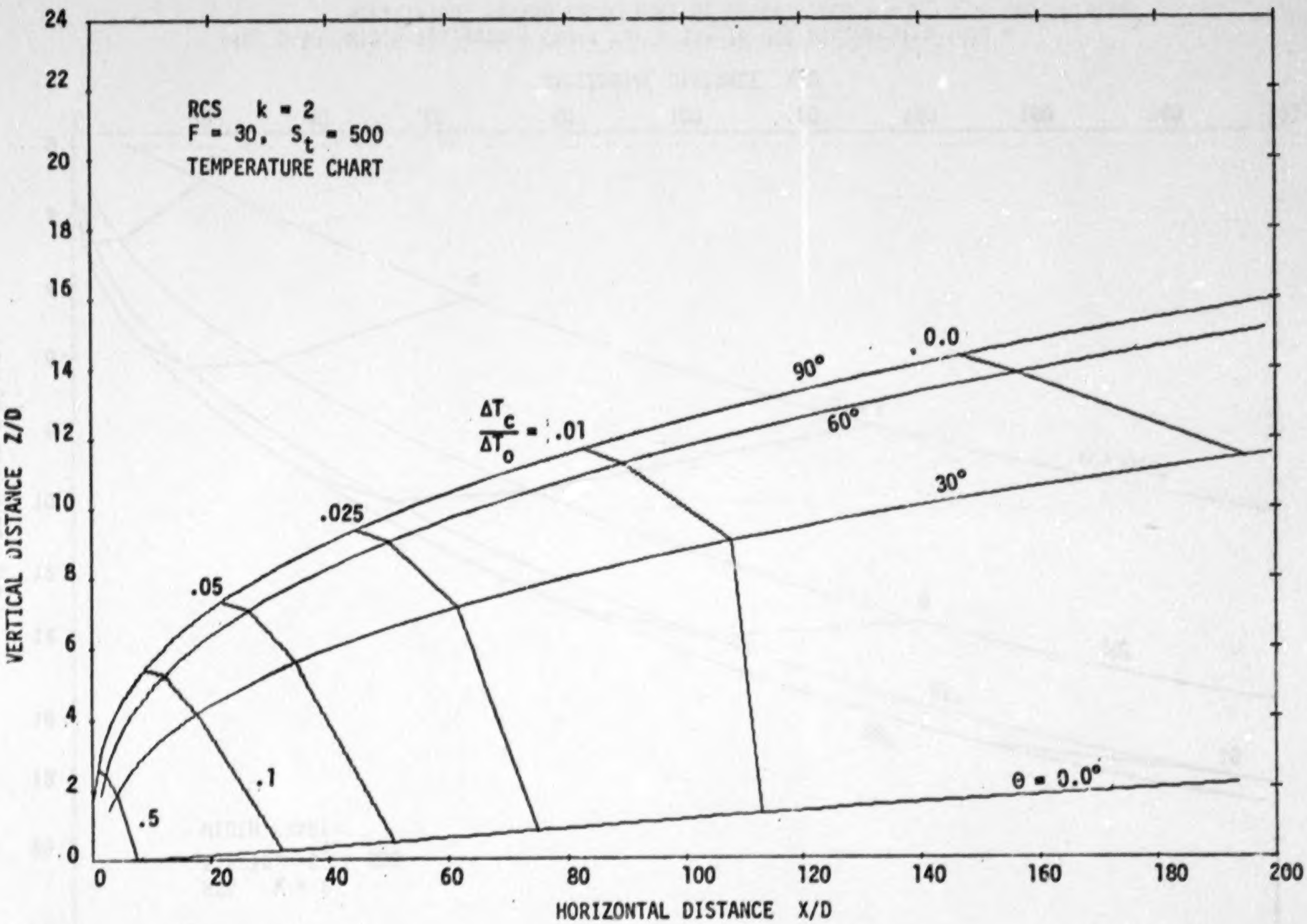

Fig. D-11 Temperature-Trajectory Chart for a Single Jet Discharging into a Stratified, Moving Large Body of Water: RCS k = 2, S_t = 500, F = 30

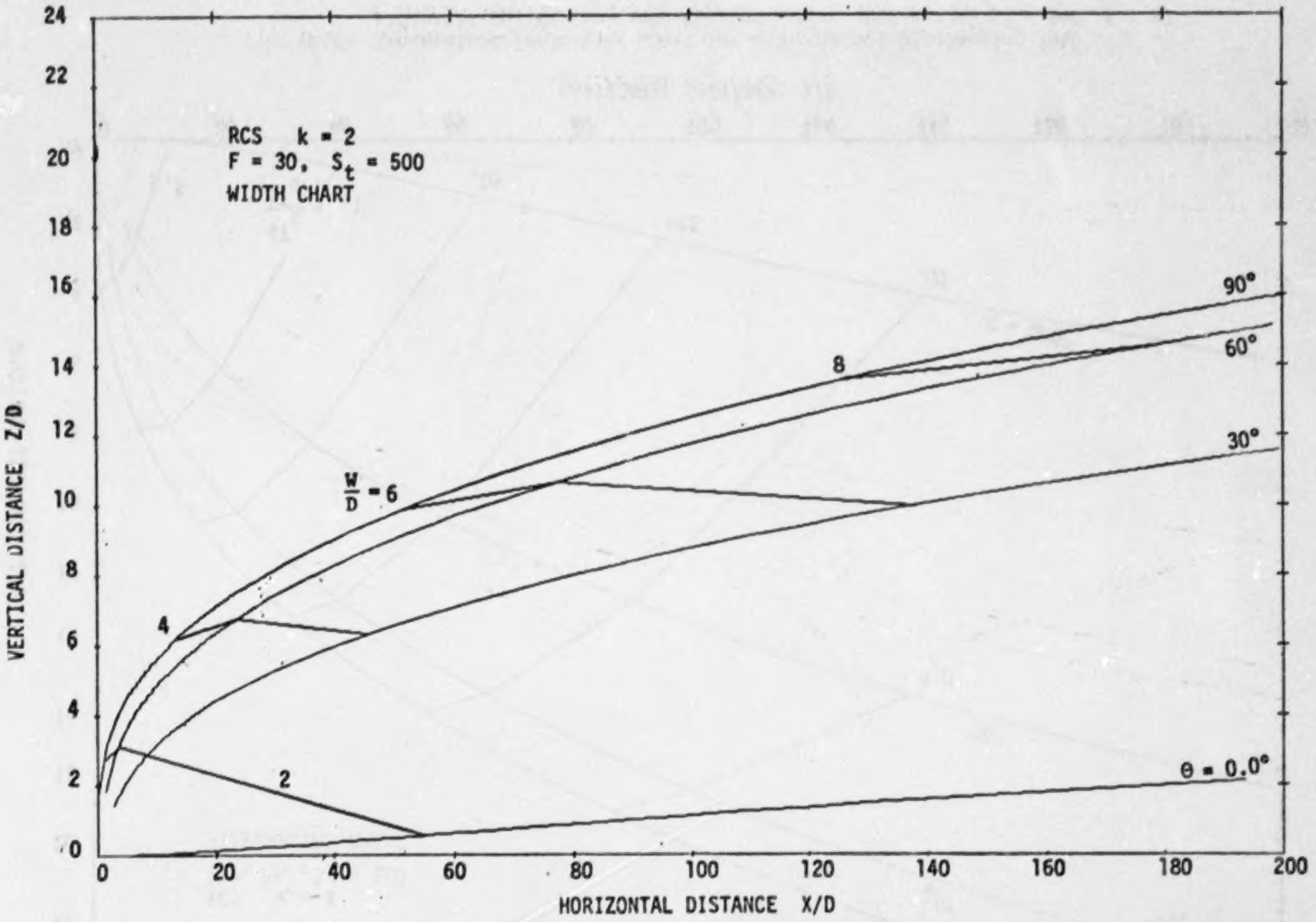

Fig. D-12 Width-Trajectory Chart for a Single Jet Discharging into a Stratified, Moving Large Body of Water: RCS k = 2, S_t = 500, F = 30

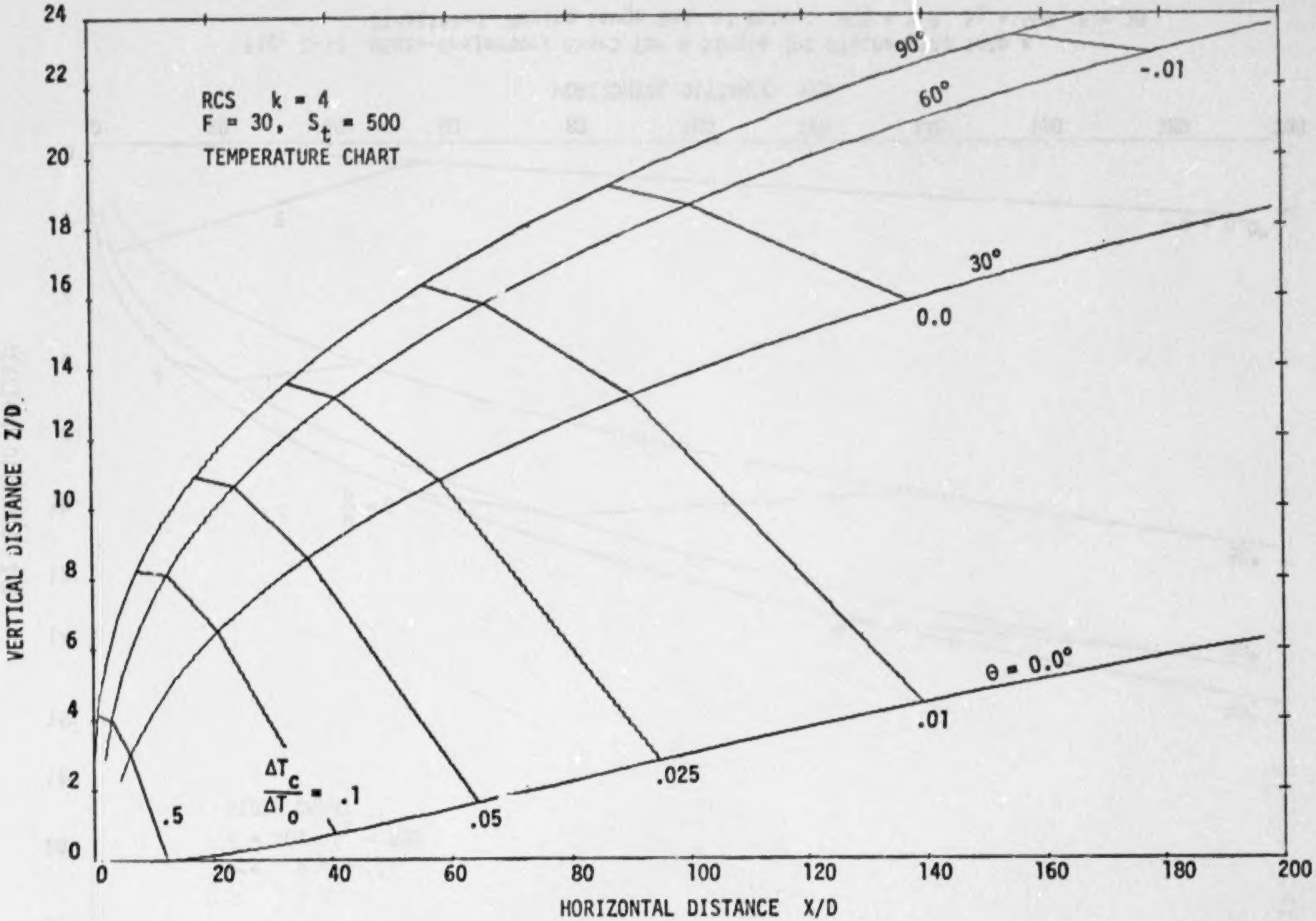

Fig. D-13 Temperature-Trajectory Chart for a Single Jet Discharging into a Stratified, Moving Large Body of Water: RCS k = 4, S_t = 500, F = 30

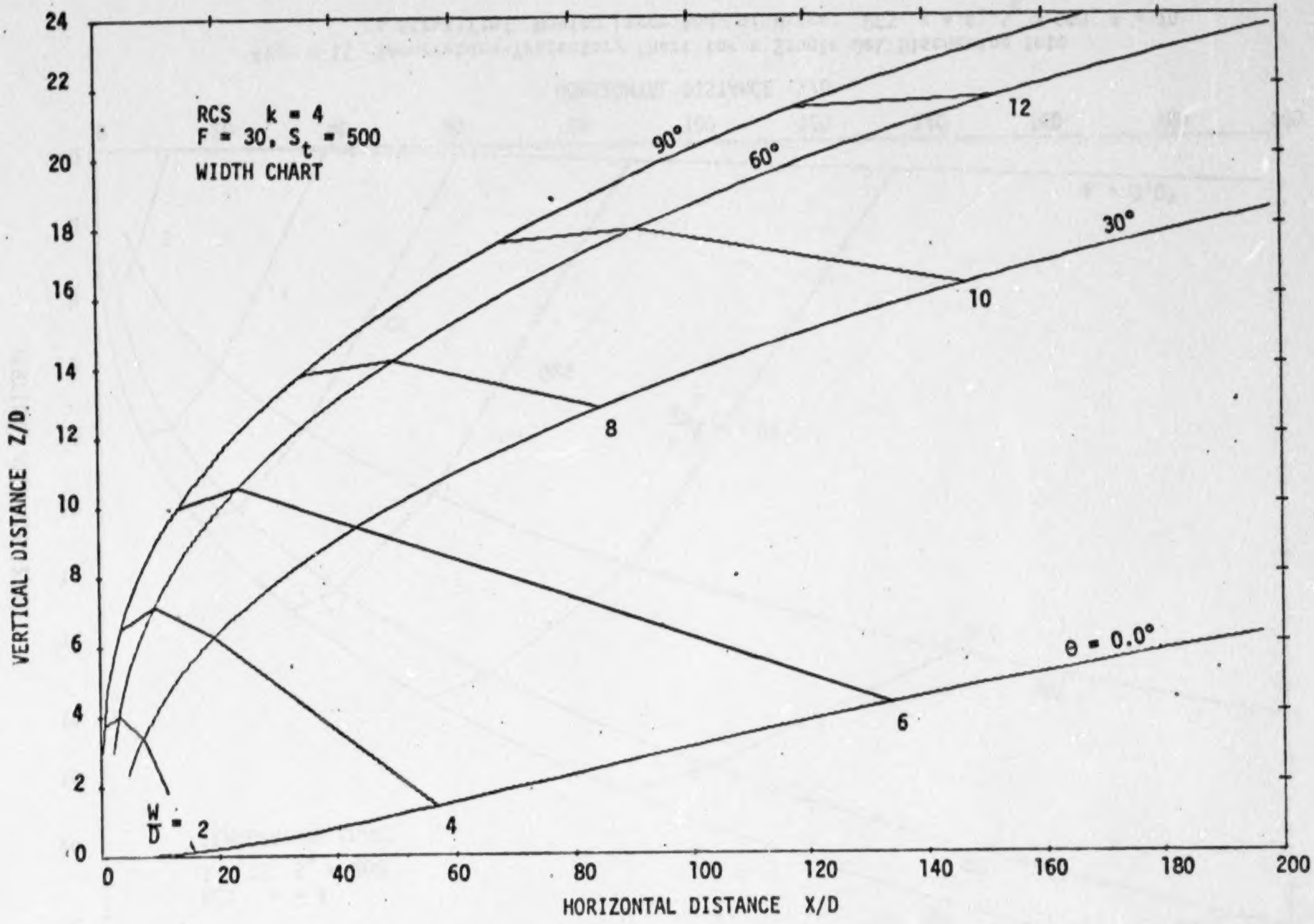

Fig. D-14 Width-Trajectory Chart for a Single Jet Discharging into a Stratified, Moving Large Body of Water: RCS $k = 4$, $S_t = 500$, $F = 30$

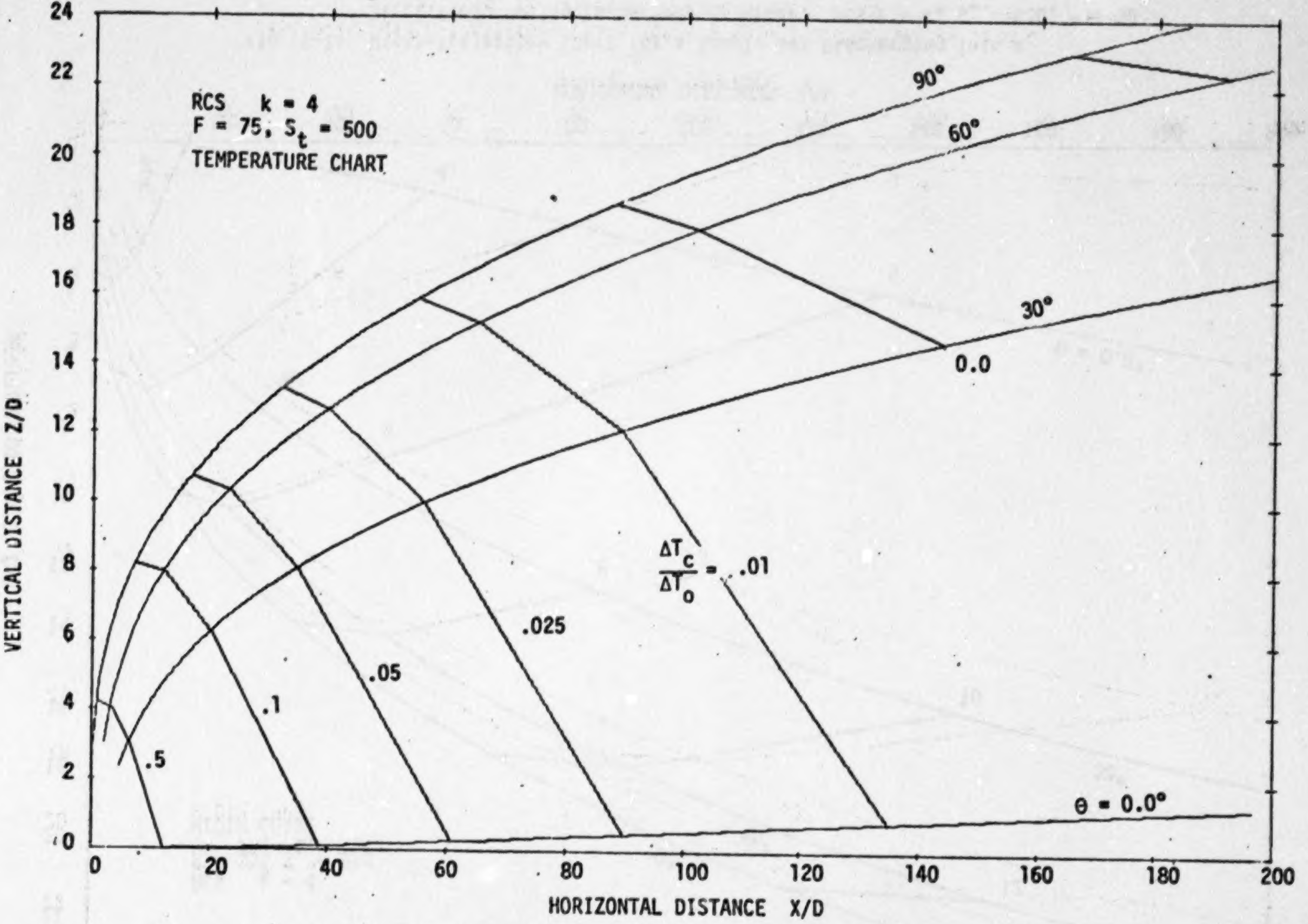

Fig. D-15 Temperature-Trajectory Chart for a Single Jet Discharing into a Stratified, Moving Large Body of Water: RCS k = 4, S_t = 500, F = 75

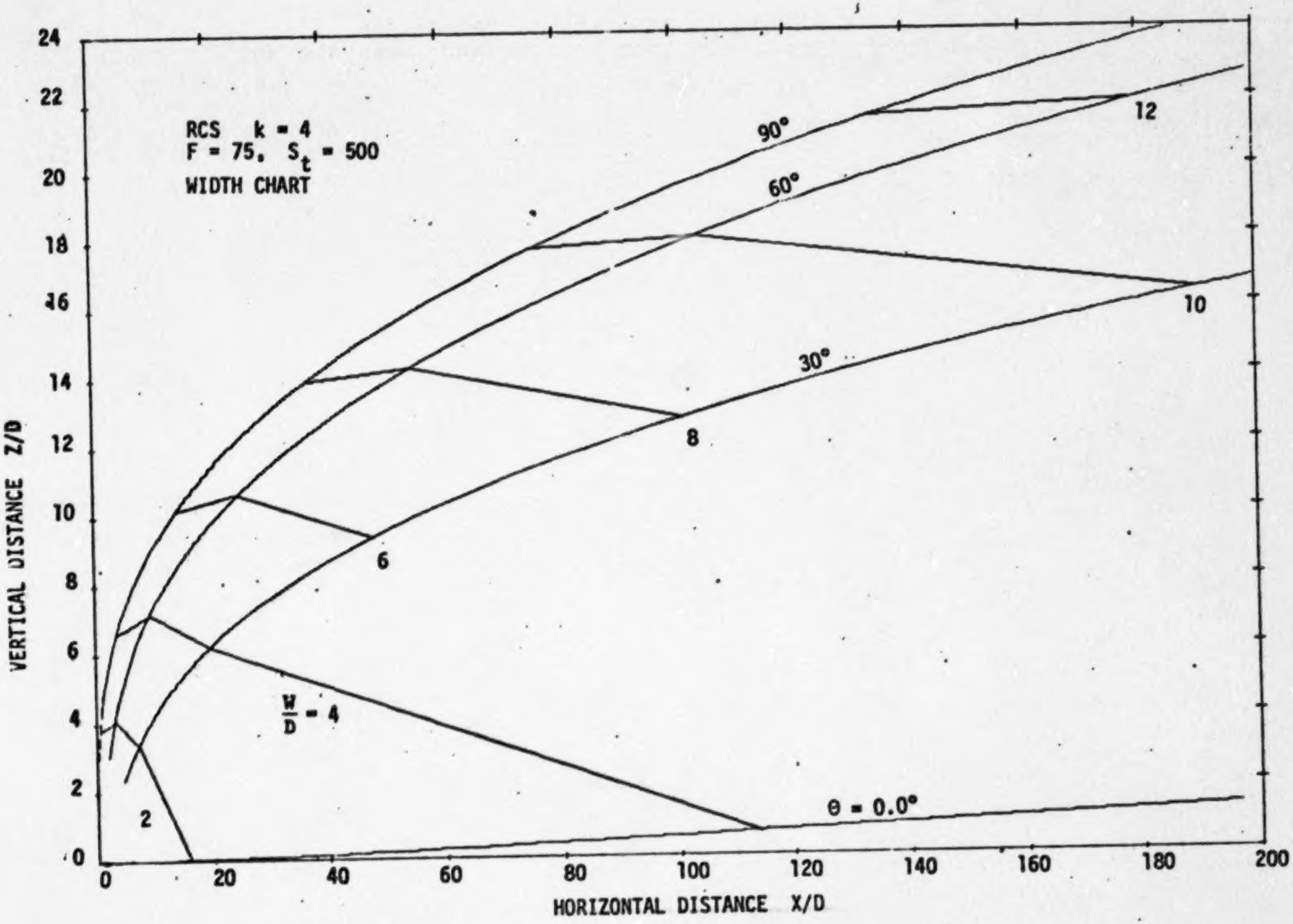

Fig. D-16 Width-Trajectory Chart for a Single Jet Discharging into a Stratified, Moving Large Body of Water: RCS k = 4, S_t = 500, F = 75

APPENDIX E

Nomograms for Vertical Discharge into Shallow, Stagnant Water (RNN, shallow discharge)

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TABLE V

Figure Numbers Corresponding to Plume Behavior for a Single Port Diffuser Discharging Vertically Upward into Non-Stratified, Stagnant, Shallow Body of Water

Discharge Depth Z/D	F = 1, 5, 25, 100		Isotherms	
	Centerline Temperature	Surface Temperature	F = 45	F = 51
5	E-3			E-6
8.4			E-5	
10	E-2	E-4		
40	E-1			

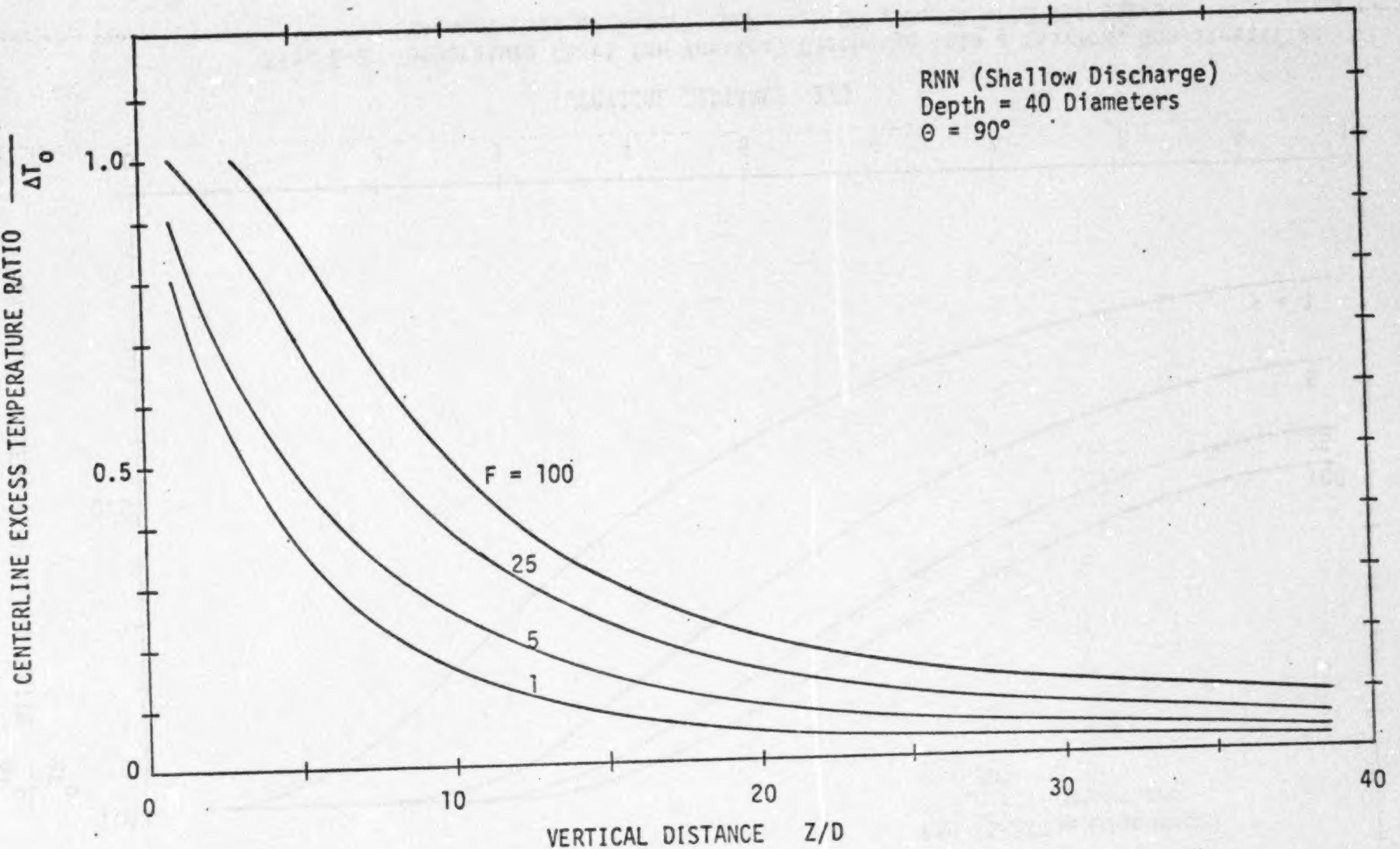

Fig. E-1 Temperature Chart for Vertical Discharge into a Shallow, Non-Stratified, Stagnant Body of Water: RNN, Θ = 90°, Depth = 40 Diameters

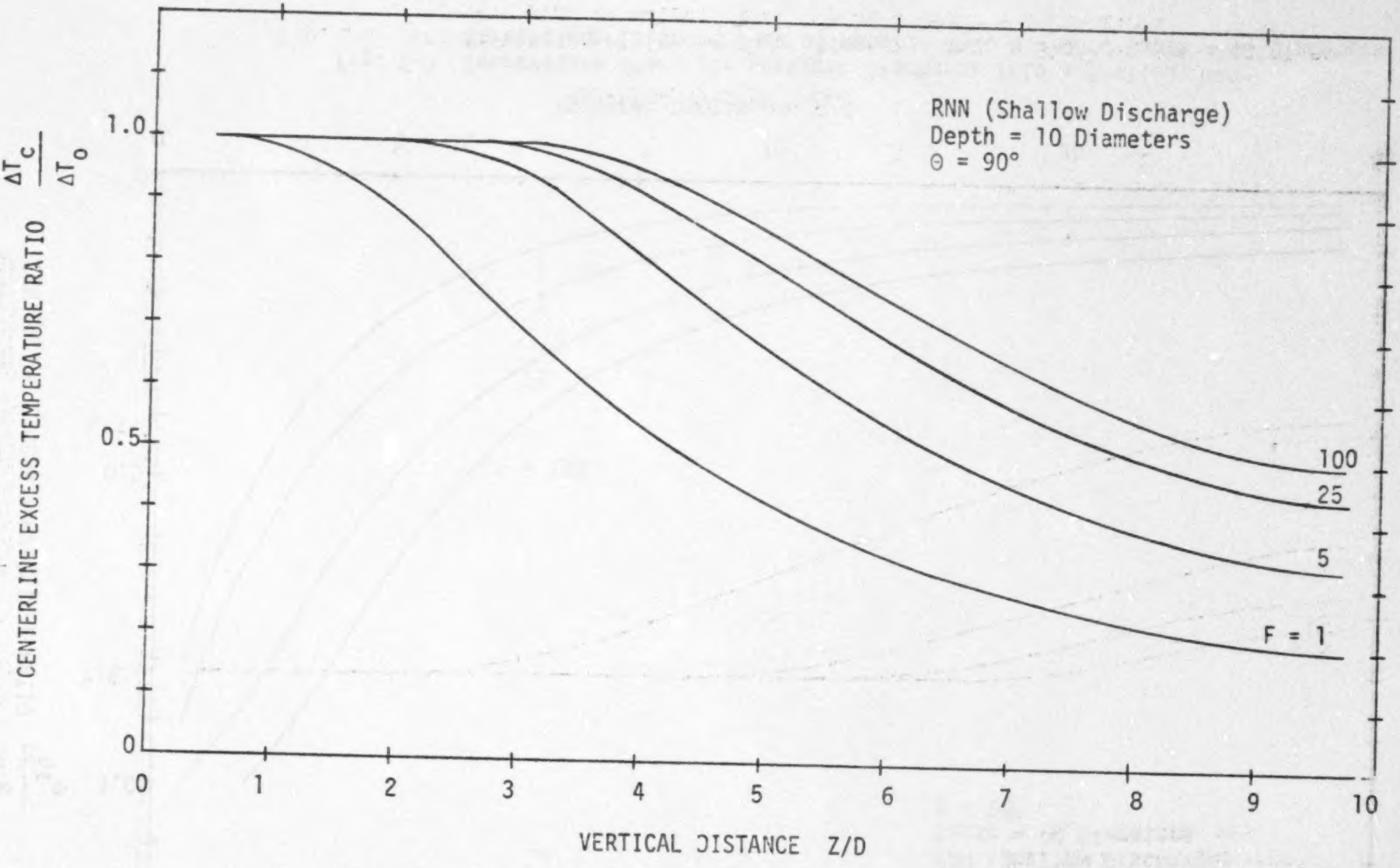

Fig. E-2 Temperature Chart for Vertical Discharge into a Shallow, Non-Stratified Stagnant Body of Water: RNN, $\Theta = 90°$, Depth = 10 Diameters

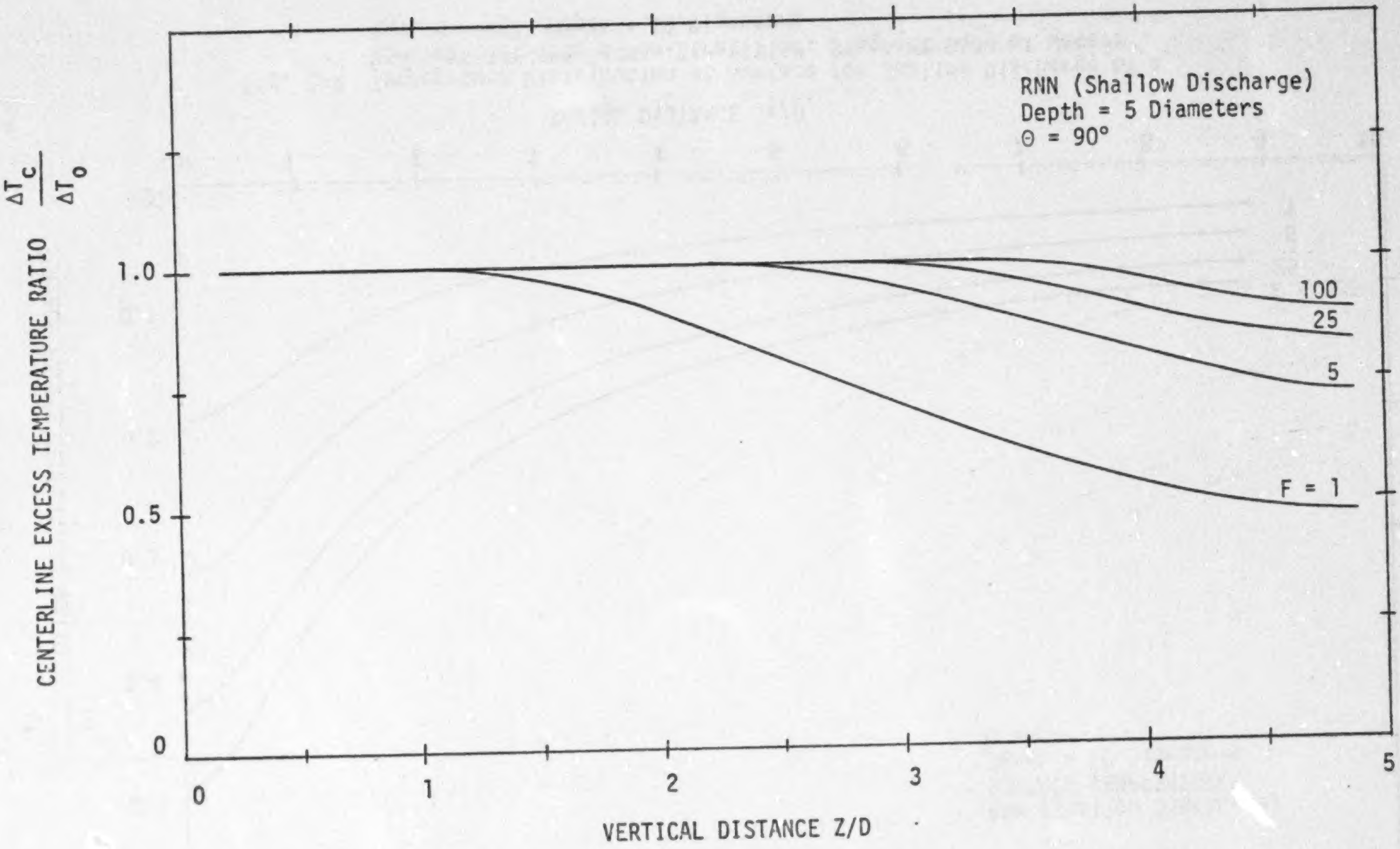

Fig. E-3 Temperature Chart for Vertical Discharge into a Shallow, Non-Stratified, Stagnant Body of Water: RNN, $\Theta = 90°$, Depth = 5 Diameters

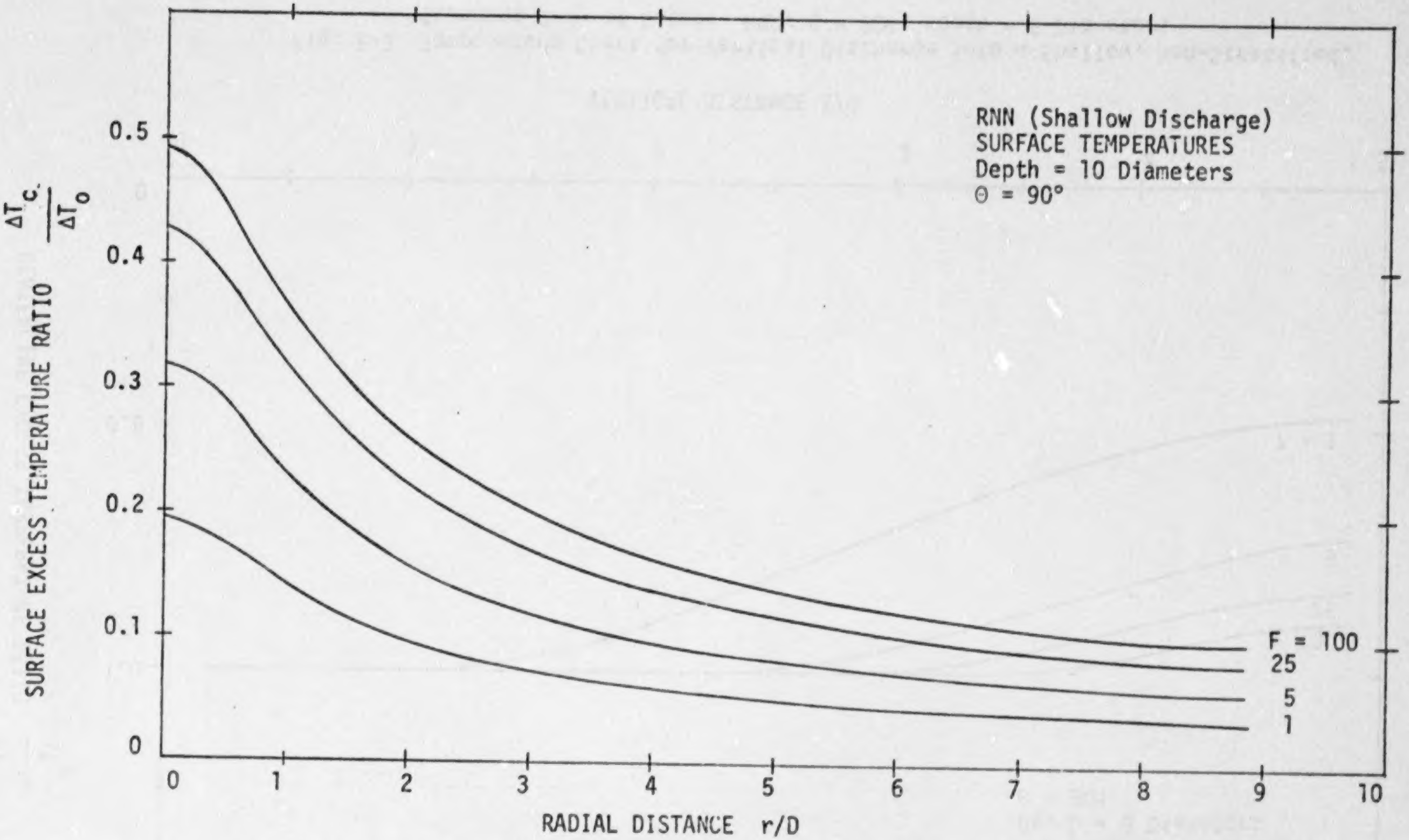

Fig. E-4 Temperature Distribution at Surface for Shallow Discharge of a Vertical Jet into a Non-Stratified, Stagnant Body of Water: RNN, $\Theta = 90°$, Depth = 10 Diameters

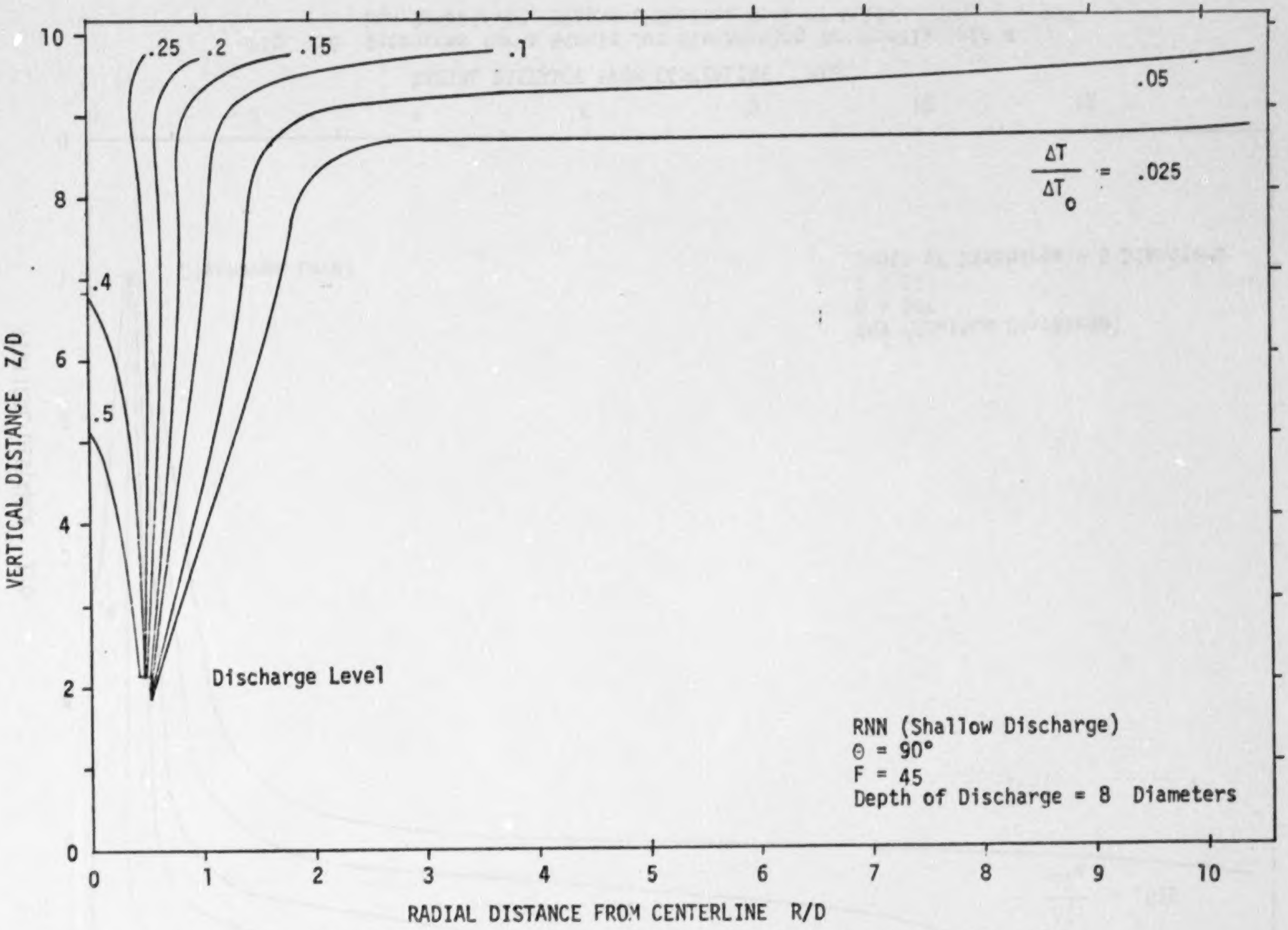

Fig. E-5 Isotherms for a Single Jet Discharging Vertically into a Non-Stratified, Stagnant Shallow Body of Water: RNN Θ = 90°

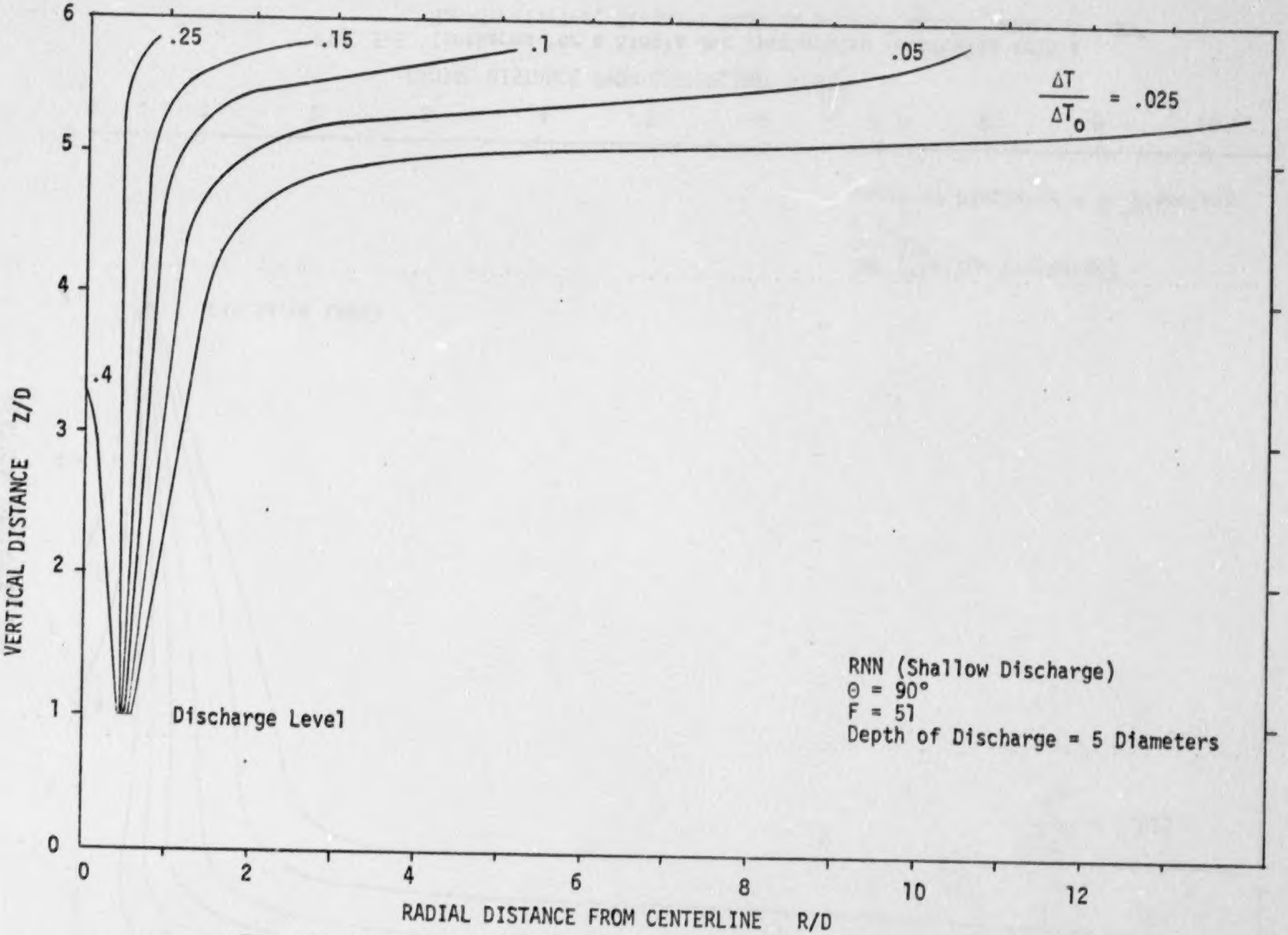

Fig. E-6 Isotherms for a Single Jet Discharging Vertically into a Non-Stratified, Stagnant Shallow Body of Water: RNN Θ = 90°

APPENDIX F

Auxiliary Materials to Aid in Solving Problems

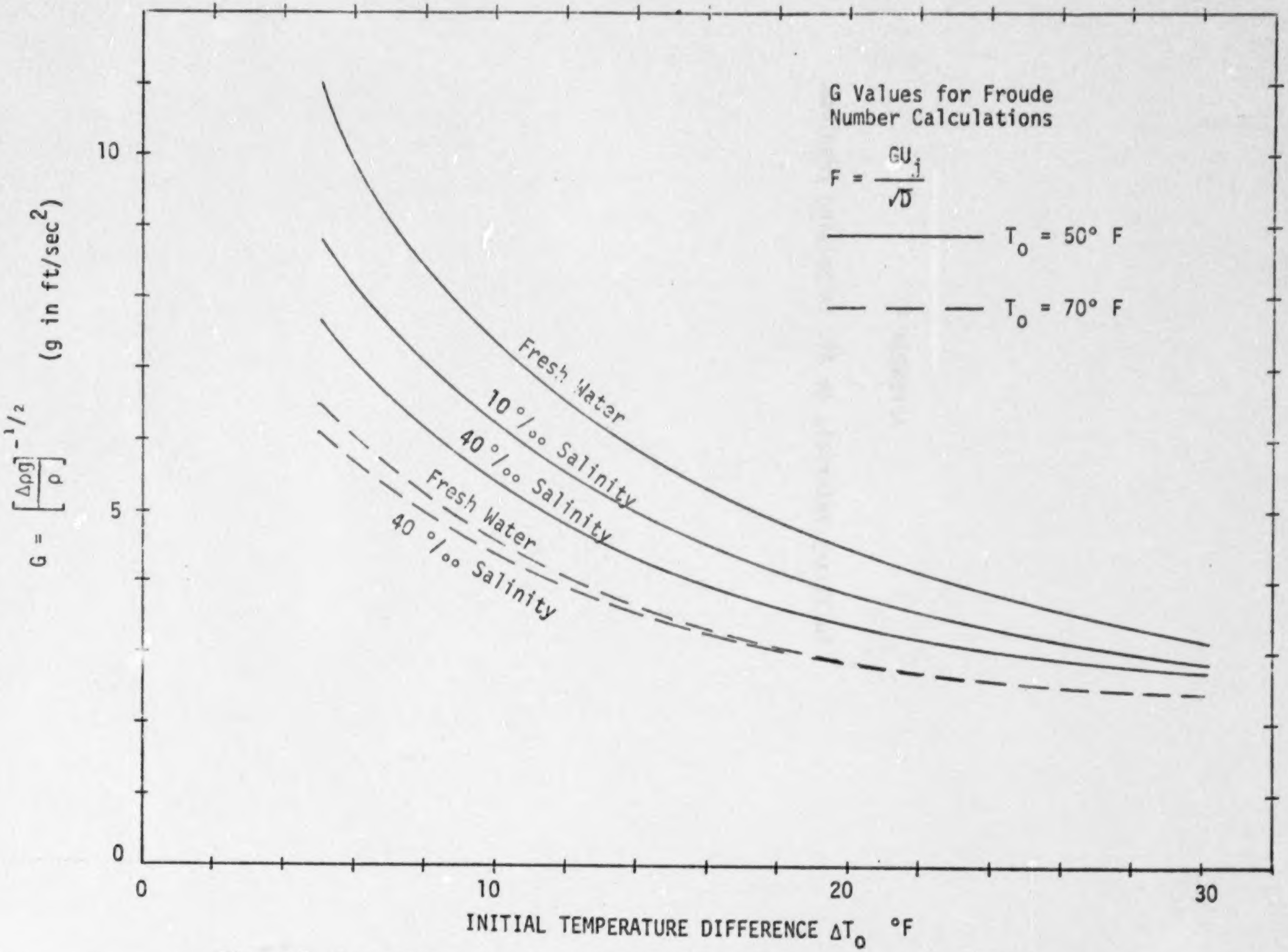

Fig. F-1 Temperature-Density Relations for Froude Number Calculations

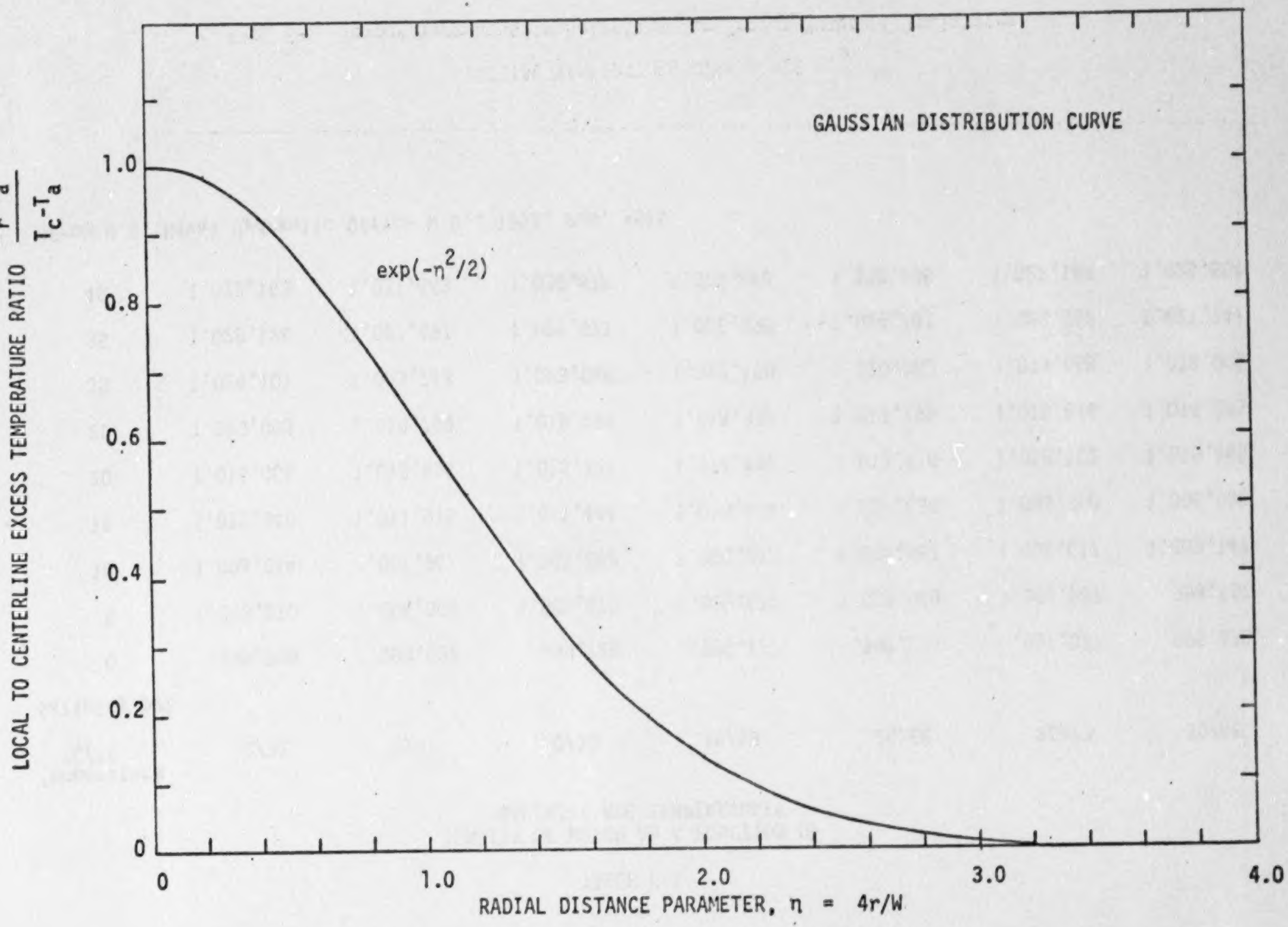

Fig. F-2 Gaussian Distribution Curve used to find Off-Centerline Temperatures

TABLE F-1

DENSITY OF WATER AS A FUNCTION OF SALINITY AND TEMPERATURE*

Temperature °C/°F	0/32	5/41	10/50	15/59	20/68	25/77	30/86
Salinity ppt							
0	.999,868	.999,992	.999,728	.999,127	.998,234	.997,077	.995,678
5	1.003,970	1.004,006	1.003,670	1.003,012	1.002,068	1.000,867	.999,567
10	1.008,014	1.007,967	1.007,562	1.006,847	1.005,857	1.004,617	1.003,147
15	1.012,840	1.011,915	1.011,444	1.010,674	1,009,638	1.008,360	1.006,858
20	1.016,065	1.015,858	1.015,321	1.014,496	1.013,416	1.012,102	1.010,568
25	1.020,083	1.019,799	1.019,198	1.018,320	1.017,196	1.015,846	1.014,283
30	1.024,101	1.023,743	1.023,080	1.022,150	1.020,983	1.019,598	1.018,008
35	1.028,126	1.027,697	1.026,971	1.025,990	1.024,781	1.023,362	1.021,747
40	1.032,163	1,031,663	1.030,878	1.029,846	1.028,595	1.027,144	1.025,504

*From U.S. Naval Hydraulic Office W.D., 1952, Pub. #615

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